

Human-friendly Robotic Manipulators

Safety and Performance Issues in Controller Design



Tadele Shiferaw Tadele

**HUMAN-FRIENDLY ROBOTIC MANIPULATORS:
SAFETY AND PERFORMANCE ISSUES
IN CONTROLLER DESIGN**

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DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
prof. dr. H. Brinksma,
on account of the decision of the graduation committee,
to be publicly defended
on Friday 07 November 2014 at 12:45

by

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in Addis Ababa, Ethiopia.

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To my parents: Shiferaw Tadele and Shitaye Tadesse

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SUMMARY

Decades have gone since robotic technology was adopted in the factory floors to facilitate cost-effective and reliable manufacturing. Successive improvements that focus on cost reduction, flexibility enhancement and lifetime extension have resulted in millions of tireless robots in our industries. Recently, different social, economic and political factors have pushed robotic technology outside the factory floors and into new application areas like agriculture, medical, rescue, personal care, entertainment, disaster response and military. This thesis focuses on personal care robots where a domestic robot with movement and manipulation capabilities operate in a human present environment to provide non-critical assistance for users.

One social challenge whose negative effects can be alleviated by using these personal robots is the rapid rate of aging in the world. The ratio of the elderly population above the age of 65 currently stands around 11% and in 20 years it is expected to double. This will definitely put a tremendous pressure on the net productivity of the working society and providing necessary care for the elderly will demand a high healthcare cost. With such challenge in mind, Bobbie project was started to come up with systematic methodology for an efficient and economically viable design of robots that can provide basic care in domestic environments.

The success of domestic robots as a human assistant is greatly influenced by their operational safety. This thesis highlighted this concern and presented a comprehensive overview of safety issues in a typical domestic robot system. The concept of functional system safety was used to address the safety of a complex robotic system by decomposing and analyzing the problem at a subsystem level. Safety regions in world modeling, sensor fusion for dependable understanding of the unstructured environment, lightweight and compliant mechanical design, passivity based control system and quantitative metrics used to assert safety are some important points discussed in the safety review.

The research focus of this dissertation is on controller design of manipulators against two conflicting requirements: motion performance and safety. Human-friendly manipulators exhibit a lightweight design and often include compliant behavior injected via an impedance controller. Another crucial consideration during the design of controllers for human-friendly manipulators is operational stability during interaction with unknown environments and this can be achieved by using

passivity based design. Thus a passivity based interaction controller that combines these two controller design aspects has become a widely adopted control scheme of such manipulators. Effective motion based manipulation using the impedance controller requires a highly stiff behavior while important safety requirements are met with compliant behaviors. On the basis of this intuitive observation, this thesis identifies suitable approaches that identify the appropriate compliance and damping behavior of an impedance controlled manipulator for a given performance and safety requirement. A frequency domain closed loop system analysis was adopted to determine appropriate impedance parameters to achieve a desired performance on simple manipulators and later the methodology was extended for non-linear multi-DOF manipulators by using energy centered inertial tensor comparisons. The safety based design begun by choosing suitable metrics that use energy and power for quantification of safety levels and then the controller impedance parameters were determined based on the allowed tolerance values of the metrics. Both design concepts were validated with simulation and experimental results.

Domestic robots built for the purpose of providing a comprehensive non-critical assistance often have a holistic design where the complete robot is built as one unit. In order to simplify the complexity of such robot designs, the personal robot built as part of this research project followed a modular design approach where the complete robot is built as an interconnection of exchangeable components. This design strategy is widely used in the IT, automotive and construction industries and is credited with minimizing development time, driving innovation and reducing cost. Bobbi-UT was built by interconnecting a mobile platform, a torso, a robotic arm and a humanoid head. The decomposition of the robot into different subcomponents was done on the basis of functional modularity concept where each module has a unique functional contribution in the system. The robotic arm, mobile platform, humanoid head and torso were used for manipulation, navigation, human detection and storage respectively. The mechanical and electrical interfaces between the components is an important component of modular systems and an effort was exerted to design an extendable interface for Bobbie-UT. Another important consideration in Bobbie-UT was the development of component based software to implement a reconfigurable and adaptable software with similar architecture across the different modules.

SAMENVATTING

Decennia geleden reeds is de inzet van robottechnologie op de werkvloer in fabrieken aangevangen om kosteneffectieve en betrouwbare productie te vergemakkelijken. Opeenvolgende verbeteringen die zich hebben gericht op kostenreductie, verbetering van de flexibiliteit en verlenging van de levensduur, hebben geleid tot miljoenen onvermoeibare robots in onze industrie. Verschillende sociale, economische en politieke factoren hebben er onlangs toe geleid dat robottechnologie ook buiten de fabrieksvloeren toepassing vindt, in nieuwe gebieden, zoals de landbouw, medisch, in reddingsoperaties, ten behoeve van persoonlijke verzorging, entertainment, rampenbestrijding en defensie. Dit proefschrift richt zich op robots voor persoonlijke verzorging, waarbij een robot in een huiselijke omgeving niet-essentiele hulp biedt aan gebruikers door zich te verplaatsen en met manipulatie-capaciteiten, in een omgeving waarin mensen aanwezig zijn.

Een sociale uitdaging waarvan de negatieve effecten kunnen worden verminderd door het gebruik van deze persoonlijke robots is de snelle vergrijzing in de wereld. Het aandeel ouderen boven de 65 jaar in de totale bevolking bedraagt momenteel ongeveer 11 % en zal in 20 jaar naar verwachting verdubbelen. Dit zal zeker een enorme druk gaan geven op de productiviteit van de werkende samenleving en het voorzien in de nodige zorg voor ouderen zal leiden tot hoge kosten. Met deze uitdaging in het achterhoofd werd het Bobbie project gestart, om te komen tot een systematische methodologie voor een efficiënt en economisch aantrekkelijk ontwerp van robots die basiszorg kunnen bieden in een huiselijke omgeving.

Het succes van robots als assistenten voor de mens in een huiselijke omgeving wordt sterk beïnvloed door hun operationele veiligheids-garantie. Dit proefschrift belicht deze zorg en presenteert een uitgebreid overzicht van de veiligheidsproblemen in een typisch thuis-robot-systeem. Het begrip functionele veiligheid wordt gebruikt om de veiligheid van een complex robotsysteem te onderzoeken door het op subsysteem-niveau te ontleden en analyseren. Veilige gebieden in door de robot geconstrueerde wereld-modellen, sensor fusie voor het krijgen van een betrouwbaar inzicht in de ongestructureerde omgeving, lichtgewicht en compliante mechanische ontwerpen, passiviteit-gebaseerde besturingen en kwantitatieve maatstaven om de veiligheid te bepalen zijn enkele van de van belang zijnde punten die worden besproken in het overzicht van veiligheidsaspecten.

Het zwaartepunt van het onderzoek in dit proefschrift ligt bij het ontwerp van de regeling van de manipulators, welke aan twee tegenstrijdige eisen dient te voldoen: nauwkeurig bewegen en veilig gedrag. Mensvriendelijke manipulators kenmerken zich door een lichtgewicht ontwerp en bevatten vaak compliant gedrag, gerealiseerd via een impedantie-regeling. Een ander belangrijk punt bij het ontwerpen van regelaars voor mensvriendelijke manipulators is operationele stabiliteit bij interactie met een onbekende omgevingen en dit kan worden bereikt door op passiviteit gebaseerd ontwerp. Dus een op passiviteit gebaseerd interactie-regeling, welke deze twee regelaar-ontwerp aspecten combineert, is uitgegroeid tot een vaak toegepaste regeling van dergelijke manipulators. Effectieve manipulatie met behulp van de impedantie-regelaar vereist een zeer stijf gedrag, terwijl aan belangrijke veiligheidseisen wordt voldaan met compliant gedrag. Op basis van deze intuïtieve waarneming worden in dit proefschrift geschikte benaderingen geformuleerd die de juiste compliantie en dempingseigenschappen van een impedantie-geregelde manipulator voor een bepaalde prestatie en veiligheidsvereiste identificeren. Een frequentie-domein analyse van het gesloten lus systeem is gebruikt om voor eenvoudige manipulators de juiste impedantie parameters bepalen om de gewenste prestaties te behalen. Daarna werd de methode uitgebreid voor niet-lineaire manipulators door energie-gerichte traagheids-tensoren te vergelijken. Het veiligheid gebaseerde ontwerp is aangepakt door te kiezen voor geschikte metrieken die energetisch vermogen en kracht behelzen te gebruiken voor de kwantificering van de veiligheidsniveau. Vervolgens zijn de impedantie-regelaar parameters bepaald op basis van de toegestane tolerantie waarden van de metriek. Beide concepten werden gevalideerd met simulatie en experimentele resultaten.

Thuis-robots die worden gebouwd ten behoeve van het verstrekken van veelomvattende niet-kritische hulp hebben vaak een holistisch ontwerp: de volledige robot is gebouwd als een eenheid. Om de complexiteit van dergelijke robotontwerpen te vereenvoudigen is bij de bouw van de persoonlijke robot die onderdeel vormt van dit onderzoek een modulaire aanpak gevolgd, waarbij de volledige robot is ontstaan door het combineren van verwisselbare componenten. Deze ontwerpstrategie wordt veel gebruikt in de IT-, automobiel- en de bouwsector en wordt gewaardeerd vanwege het minimaliseren van de ontwikkelingstijd, het stimuleren van innovatie en het verminderen van kosten. Bobbi-UT werd gebouwd door het samenstellen van een mobiel platform, een romp, een robotarm en een humanode hoofd. De ontleding van de robot in verschillende subcomponenten gebeurde op basis van functionele modulaire concepten, waarbij elke module een unieke functionele bijdrage levert aan het systeem. De robotarm, het mobiele platform, het humanode hoofd en de romp werden gebruikt voor respectievelijk de manipulatie, de navigatie, de detectie van mensen en opslag. De mechanische en elektrische interfaces tussen de componenten is een belangrijk onderdeel van modulaire systemen en daarom is een aanzet gedaan tot een uitbreidbare interface voor Bobbie-UT. Een andere belangrijke overweging bij Bobbie-UT was de ontwikkeling van een component-gebaseerde software om te komen tot herconfigureerbare en flexibele software met een gelijkaardige architectuur in verschillende modules.

LIST OF ACRONYMS

CBSD	Component Based Software Development
DOF	Degree of Freedom
HIC	Head Injury Criteria
HIP	Head Injury Power
IEC	International Electrotechnical Commission
ISO	International Standard Organization
MTBI	Mild Traumatic Brain Injury
OROCOS	Open Robot Control Software
PD	Proportional Derivative
PID	Proportional Integral Derivative
ROS	Robot Operating System
SEA	Series Elastic Actuation
VIA	Variable Impedance Actuation

CONTENTS

1	Introduction	1
1.1	Human-friendly manipulators	3
1.2	Research Outline	4
1.3	Thesis Outline	7
2	Safety in Domestic Robotics	9
2.1	Introduction	10
2.2	Safety Criteria and Metrics	11
2.3	Mechanical Design and Actuation	16
2.4	Controller Design	18
2.5	Sensing, Perception and Motion Planning	20
2.6	Conclusion	25
3	Performance Based Control Design for Human-friendly Manipulators	27
3.1	Introduction	28
3.2	Background Concepts	29
3.3	Performance Based Impedance Control for 1 DOF Manipulators	36
3.4	Extension to Multi-DOF Manipulators	39
3.5	Simulation and Experiment Results	44
3.6	Conclusion	49
4	Safety Aware Controller Design for Human-friendly Manipulators	51
4.1	Introduction	52
4.2	Design Considerations	53
4.3	Safety aware impedance controller for Simple Manipulators	54
4.4	Extension to Multi-DOF Manipulators	56
4.5	Simulation and Experiment Results	59
4.6	Conclusion	64
5	Towards a Modular Domestic Robot: Bobbie-UT	65
5.1	Introduction	66
5.2	Modularity in domestic service robots	67

5.3	Bobbie-UT	68
5.4	Discussion and Conclusion	78
6	Conclusions and Recommendations	81
6.1	Conclusions	81
6.2	Recommendations	85
I	Appendix	87
A	Modeling Aspects of Serial Robotic Manipulators	89
A.1	Modeling	89
A.2	Computations	92
B	Energy tank based controller implementation	95

CHAPTER 1

INTRODUCTION

For centuries, human beings have used technology to introduce diverse skill sets, knowledge, methodologies and products which ultimately shaped our world. Starting from the simple water clocks of ancient Egypt, technology has experienced an immense expansion and currently reached exciting levels in communication, computing, genetics, medicine, physics, material science, construction, transportation, aviation, optics, engineering and many more. Humans' endeavor to solve contemporary as well as foreseeable problems and improve previously devised solutions has been the main driving force behind this continuous growth of technological achievements.

Robotic technology has also gone through a similar progressive development to establish itself as an integral sector with a wide range of applications. The construction of human-like dolls which evolved from a simple design in first century A.D. to steam-powered motion capability in the late 19th century laid the foundation for the great leap that followed [53]. In the 1950s the first digitally programmable robot was designed and commercialized, thereby paving the way for a wave of industrial robots that revolutionized the way manufacturing is carried out [77]. The International Federation of Robotics which tracks the commercial flow of these industrial robots estimates the total number of operational robot units at the end of 2012 to be more than 1.2 million and forecasts upwards of 1.6 million units by 2016 [136].

Driven by the expansion of industrial robots and advancements in supporting technologies, the robotics community has given an increased attention towards the adoption of robotic technology outside its industrial setting. This has in turn revealed the potential of robots to provide invaluable contributions in application domains such as agriculture, medicine, home-care, inspection, entertainment, logistics, emergency response and others. This thesis highlights the use of robots for

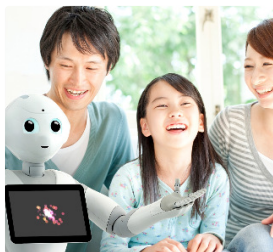
personal-care purpose and this includes all service robots which directly perform or assist actions that contribute towards improvement of the quality of life of an individual [74]. A domestic robot is a personal care robot which operates indoors and is often used to provide non-critical assistance in the day to day activities of a user. Possible applications of these robots in home environments include entertainment, security, education, hazard detection and assist in daily chores such as cooking and cleaning. Furthermore, these domestic robots can provide services like cleaning and transportation around office environments or perform specific duties as museum guides or customer communication portals. See Figure 1.1.



(a)



(b)



(c)



(d)



(e)

Figure 1.1: Service robots used in different applications: (a) Cleaning robot Roomba (b) Cooking robot of Motoman (c) Social companion robot Pepper (d) Indoor service robot from Hollywood movie Rocky 4 (1985) (e) Museum tour guide Jinny

There are a number of demographic, social and economic factors that have contributed to the expansion of personal care robots in the last decade. One frequently mentioned factor is the upsurge in the healthcare cost in the developed world due to the increasing number of aging population. For example, inflation-adjusted comparison of the health care cost for the elderly in the United States of America has shown an increase of \$100 billion between 2001 and 2011 [130]. Japan and Europe are also experiencing similar problems due to the increasing share of the elderly among the total population. Personal care robots have been proposed as a viable solution to deal with this challenge and different aspects of their operation such as use-cases, ethical impact, legal issues and social influence have been investigated by researchers and manufacturers [12, 41, 55, 129, 191].

A general design guideline of these service robots often involves implementing the required functional requirements such as manipulation, mobility, perception and world modeling. Moreover, their existence in human present environments imposes a strict safety guideline that should be considered in the robot design. There are still a number of design challenges that should be addressed by the robotics community to satisfy these numerous and sometimes conflicting requirements. For example, a reliable understanding of the surrounding environment requires multiple sensor units and this might cause an undesirable increase in complexity of the system. In addition to the operational concerns, identifying a systematic methodology that minimizes their complexity and cost is an essential prerequisite for mass production of these robots for possible automotive like commercialization.

1.1 Human-friendly manipulators

Robotic manipulators are the core of industrial manufacturing as they facilitate efficient production on factory floors. Given a certain task and required system flexibility, the design of an industrial manipulator is influenced by the operational workspace, manipulability, payload capacity, operational speed and accuracy [36]. They operate inside a well-defined environment and are predominantly used to perform repetitive motion based tasks such as moving pre-defined items, painting and welding. Hence, they often use position controllers which in turn gives the manipulators a very stiff dynamic behavior [162]. They also exhibit a typically massive design in order to allow manipulation of heavier loads.

In addition to position guided tasks, robotic manipulators can also be used in applications like component assembly that involve direct contact with the environment. For such use-cases, it becomes essential to analyze and control the interaction between the manipulator and its environment. This mechanical interaction can be conveniently represented by power conjugated force and motion variables which are observed at the point of contact [78, 35, 176]. Thus, the control objective for interacting robots not only deals with position of the manipulator, but also the contact force at the interaction point. The force control can be implemented indirectly via an impedance controller [78] or directly by using force sensor measurement to

implement a closed-loop control [154, 103, 40, 33].

For domestic care robots, household chores such as opening doors, handling objects, cleaning tables and operating switches are impossible without a manipulator arm. Hence, a robotic manipulator is also an integral part of a care robot and its design should back a typical use-case of performing tasks in a human present unstructured area. While the basic factors that influence the design of human-friendly manipulators are similar to the industrial ones, their relatively smaller payload and high safety requirement demand a lightweight and compliant design [185, 76, 119]. Their operation surely includes interaction with various objects and thus require an interaction controller which allows a stable operation against range of environmental behaviors including cases of contact, no contact and the transition between the two. Because of the inadequacy of direct force controllers to manage unstructured environments [170] and their sensitivity to coupled instability [52, 79], impedance control is used as the interaction controller of choice in this thesis. Impedance control technique offers easier task planning and its effectiveness is reported in various applications such as human-robot cooperation, dynamic whole-body mobile manipulation, vision guided manipulation, dual-arm cooperation and human-assist systems [28, 81, 186, 43, 133, 27]. The impedance control scheme is introduced in Chapter 2 and its implementation for a real-world manipulation activity is elaborated by considering a table cleaning task in Chapter 3. Furthermore, its physically interpretable nature is exploited for a safety based controller design in Chapter 4.

In order to address stability of a robotic system during interaction, a controller design demands a proper description of the environment which in the case of human-friendly manipulators is often described as ‘unknown’. In a typical operation of the manipulator, it can be pushing a very stiff object at one instant and later move freely in a zero stiffness open space. To analyze stability of human-friendly manipulators under such a varying environmental condition, different authors have used passivity theory in the controller design [97, 3, 143, 208]. Under the methodology, the energy content of the controlled system is remains bounded and its Lyapunov stability can be guaranteed for interaction with any passive environment. An energetically consistent extension of the passivity concept into a discrete domain also allows a low-level energy monitoring which can strengthen the robustness of a human-friendly manipulator [174]. Passivity of the controlled robotic system is one of the pillars behind the controller design approach followed in this thesis and it is concisely reviewed in Chapter 3.

1.2 Research Outline

1.2.1 Bobbie Project

Similar to the trends in other developed countries, the increasing number of aging population and the difficulty in providing acceptable care to them has been recognized as a serious threat to the healthcare system in the Netherlands. Different

stakeholders have agreed on the use of robotic technology to alleviate this burden on the healthcare system and a national project “Bobbie” was started to investigate key technologies, challenges and limitations [17]. One primary problem identified is that even if all the basic technologies such as vision, software, computing and mechatronics are independently solved, they have not been combined to showcase an economically viable domestic robot industry.

The Bobbie project was then started with a general goal of using standardized architectures to design robotic systems that can safely work in a care situation. The motivation behind the standardization was derived from the personal computer markets that proliferated after the introduction of the IBM standard PC architecture. Comparing the two products, robots are at the stage of computers before the IBM standard and the adoption of standardized interfaces for modular design is expected to open up the potential of domestic robots. The long term vision of this standardization effort is a plug-and-play robotics where different companies produce interchangeable robotic parts which can confer to the defined standards. With well-defined and mature interfaces, application developers can also build commercial software products that can enable a given task execution by the robot.

The project consortium involved three technical universities: Delft University of Technology, Eindhoven University of Technology and University of Twente, and also a number of local industrial partners. All members take part in the research activities of the project and the use of its output for possible commercialization of robotic products was an additional target for the industrial affiliates. The first stage of the project involves definition of mechanical, electrical and software standards that should be followed by all parties. Afterwards, each consortium member was given a specific focus area of the general robot design plan and output results were expected to be shared for possible reused by other partners.



Figure 1.2: Bobbie project: merging partner expertise in a modular domestic robot design

1.2.2 Research Objectives

Within the project, the Robotics and Mechatronics group at the University of Twente was assigned to lead the study into the control of robotic manipulators during their operation in a 3D environment. The research on controller design for human-friendly robotic manipulators was going side-by-side with the building of a research robot Bobbie-UT that satisfies the design requirements set by the project.

Specific goals of the thesis are,

- investigating current trends, challenges and methodologies of analyzing, describing and improving safety in domestic robots
- analyzing the effect of compliance on the performance of manipulators and then using the results to design a controller based on desired performance requirements
- applying insights from safety analysis of domestic robots to realize a safe human-friendly robotic manipulator
- adopting state-of-the-art methodologies to design a modular domestic robot which allows exchange of components
- verifying design ideas with simulation and experimental verification

1.2.3 Contribution of This Thesis

Given the list of goals presented in the previous section, the expected results of this thesis work consist of a mix of both theoretical and practical outputs. While the main emphasis of the thesis lies on control of human-friendly manipulators, the complete safety review of domestic robots and the reported construction of an actual robot broadens its scope.

The controller design proposed for human-friendly robotic manipulators is an extension of the standard impedance controller design in order to explicitly address performance and safety requirements. Incorporating these requirements on the controller design results in a variable impedance controller design that demands a special implementation to ensure the passivity of the system. The robot building process offers insights into an efficient engineering methodology where different parts are assembled to form a complete product. The results of this work could be used as a basis to conduct further investigations into safety of domestic robots, controller design of human-friendly manipulators and efficient production of domestic robots.

The main contributions of the thesis are

- A comprehensive safety analysis of domestic robots covering the complete robotic system
- A passivity based variable impedance controller design that satisfies a desired tracking performance in cartesian space

- A novel safety aware impedance controller design with a generalized implementation that can avoid injury to a human in case of collision
- An onset towards a systematic and well-organized robot design technique which allows reusability of hardware as well as software components

1.3 Thesis Outline

This thesis is composed of four main chapters that focus on the main research objectives defined in the prevision section. Each chapter is prepared as a self-contained work which is based on a separate publication and the overall outline of this thesis is as follows.

Chapter 2 gives an comprehensive overview into safety of domestic robots. It is a survey of publications that address safety issues of domestic robots in their design. The chapter emphasizes on an overall system safety and presents safety challenges of a complete robotic system by categorizing its components into four main focus areas: safety criteria & metrics, mechanical design & actuation, controller design and sensing, perception & motion planning. Safety concerns of the complete robotic system is covered in the latter three groups while the first focus area reviews different norms that are used to evaluate safety.

Chapter 3 presents a performance based analysis of impedance controlled manipulators and uses frequency domain approaches to design a controller that meets the desired performance requirements. Based on motion control rules of PID controllers, it first introduces the design approach for a simplified one DOF manipulator and then later extends the methodology to a multi-DOF robotic manipulator. The compliance and the passivity of the impedance control design is evident in the design approach and then the effect of desired compliance on the dynamic behavior of manipulators is studied.

Chapter 4 uses suitable safety metrics discussed in Chapter 2 to introduce a novel safety aware impedance controller design. The proposed methodology imposes a safety based limitation on the total energy content of the impedance controlled manipulator as well as the power flow between the controller and the manipulator. The primary goal of the design is to avoid injury to a human user in case of uncontrolled impact with the manipulator by restraining the total energy and power that can be transferred to the human during the contact. The effect of this demand on the desired impedance of the manipulator and a passivity based implementation of the design is introduced first for a simple 1-DOF manipulator and then later generalized to multi-DOF robotic manipulators.

Chapter 5 highlights the design choices and tasks carried out while designing a robotic research platform Bobbie-UT. First, it establishes the advantages of modular design and component reuse on minimizing development efforts in robotics. Then, it presents the basic modular components of Bobbie-UT and discusses different development activities which were aimed at satisfying the necessary functional

and safety requirements of the components. At the end, the data processing, information communication and software development architectures that fit into the modularity and reuse oriented design are briefly discussed.

The final chapter summarizes the main contributions of this thesis and provides some suggestions for possible future extensions.

CHAPTER 2

SAFETY IN DOMESTIC ROBOTICS

“A robot may not injure a human being or, through inaction, allow a human being to come to harm.” Isaac Asimov

Different branches of technology are striving to come up with new advancements that will enhance civilization and ultimately improve quality of life. In the robotics community, a stride has been made to bring the use of personal robots in office and home environments on the horizon. Safety is one of the critical issues that must be guaranteed for the successful acceptance, deployment, and utilization of domestic robots. Unlike the barrier-based operational safety guarantee that is widely used in industrial robotics, safety in domestic robotics deals with a number of issues, such as intrinsic safety, collision avoidance, human detection, and advanced control techniques. In the last decade, a number of researchers have presented their works that highlighted the issue of safety in a specific part of the complete domestic robotics system. This chapter presents a general survey of relevant safety related publications and shows how they contribute to the overall system safety of domestic robots by grouping them into four main focus areas: safety criteria & metrics, mechanical design & actuation, controller design and sensing, perception & motion planning.

2.1 Introduction

Recent advances in robotics led to the growth of robotic application domains such as medical [173, 132, 183], military, rescue [181, 16, 131], personal care [202, 18, 73, 90] and entertainment [84, 26]. The personal care category includes a class of domestic robots which operate inside a home or office environment. Domestic robots can be with or without a manipulator but are often mobile to navigate in their human-present work area. This cohabitation of domestic robots and a human in the same environment raised the issue of safety among standardization bodies [203, 74], research communities [150, 158, 164, 134] as well as robot manufacturers [110, 1, 155, 127].

As an attribute of dependability, safety is one of the fundamental issues that should be assured for flourishing use of domestic robots in the future[2, 163]. In general, safety in domestic robotics is a broad topic that demands ensuring safety to the robot itself, to the environment and to the human user, with the latter considered the most important requirement. In a robotic system where human interaction is involved with a certain risk, it is important to do a careful robot design, taking into account the famous Murphy's law: "If something can go wrong, it will". Standard safety requirement used in robotics include a three step safety guideline: (1) risk assessment; (2) risk elimination and reduction; and (3) validation methods [203, 74, 138].

The primary risk assessment step identifies a list of tasks, environmental conditions and potential hazards that should be considered during system design. Different techniques of performing risk assessment in order to identify and methodically analyze faults in robotic systems are presented by different authors [42, 60] as well as ISO 12100 standard [87]. The following risk identification and reduction step, by itself, is an iterative three step process that include safe design to avoid or minimize possible risks, a protection mechanism for risks which can not be avoided by design and finally a warning to the user in case both design and protection failed. The final validation step establishes methods that are used to verify whether desired safety requirements are satisfied by the developed system.

Even if all the three steps are equally important to design robots that can be used in human environments, most of the safety related works in domestic robotics over the past decade focused on risk elimination and validation steps in a selected part of the total robotic system. Hence, this survey left out works related with risk assessment and covers publications that include risk elimination and validation steps of the standard robotic safety requirement in domestic robotics. For a complex domestic robot which consists of different mechanical, sensing, actuation, control system, perception and motion planning subsystems, see Figure 2.1, analysing overall safety can be done by using the concept of functional safety [172, 120]. This systematic approach allows safety evaluation of domestic robots based on standardized functional safety of each subsystem as well as the interactions that exist between them. Typical functional safety standards that can be used for safety analysis are ISO 13849: "Safety of machinery: Safety related parts of control sys-

tem” and IEC 61508: “Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems”.

This survey first presents different *safety metrics* that are used to validate safety of a domestic robot during unexpected collision between the robot and a human user. Then using a system based view of safety, the following sections discuss various safety enhancement ideas in *mechanical design & actuation*, *controller design* and *sensing, perception & motion planning* for domestic robots.

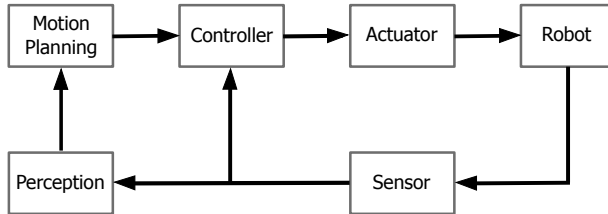


Figure 2.1: Typical robotic system

2.2 Safety Criteria and Metrics

Domestic robots require meaningful criteria and metrics in order to analyse their safety and define injury levels of potential hazardous conditions. Safety criteria define desired design requirements while the quantitative safety metrics, defined based on the criteria, are essential for providing insightful safety improvement ideas, comparing successful system implementations and assisting system accreditation. Safety metrics are in general used to identify what injury a robot might cause [67]. The safety criteria are mostly part of an international standard that is acceptable by the manufacturing industry as well as the research community.

A standard framework used when dealing with safety in robotics is risk or injury based safety requirement which requires system level analysis of safety. The International Standard Organization (ISO) uses this approach to release a set of safety requirements for robots such as ISO 10218-1-“Safety requirements for robots in manufacturing industry”. These standards are updated when needed and in the case of ISO 10218-1 a revised standard was released that deals with the emerging requirement in industrial robotics to share a workspace with humans [86]. An ISO committee has also addressed the issue of safety in personal robots and released an advanced draft of their work ISO 13482-“Safety requirements: Non-medical personal care robot” [88].

There are a number of hazards and risks which are included in the safety standard for domestic robots but contact based injuries can be divided into two types: quasi-static clamping and dynamical loading. Different subclasses of the injuries exist depending on the constraint on a human, singularity state of the robot and sharpness of the contact area [70]. The dynamic loading collision between a robot

and a human can be either a blunt impact or a sharp edge contact in which possible injuries range from soft tissue contusions and bruises to more serious bodily harm. Collision analysis and modeling for investigation of injury measurement was presented in [146] while [65] discussed details of soft tissue injuries such as penetrations and stabs using experimental tests. There is no universally accepted safety metric that measures these injuries but a number of approaches have been presented. The common safety metrics used to measure collision and clamping risks in domestic robotics can be categorized into different groups based on the parameters they use as *acceleration based*, *force based*, *energy/power based* or *other parameter based*.

2.2.1 Acceleration based

The most widely used safety metrics in domestic robotics for injuries due to collision is the acceleration based Head Injury Criteria (HIC) [189]. The metric is derived from human biomechanics data given in the Wayne State Tolerance Curve [61] and is used in biomechanics studies and accident researches in different fields such as the automotive industry. It is a measure of the head acceleration for an impact that lasts for a certain duration and is given mathematically as [57],

$$HIC_{\Delta t} = \Delta t \left[\frac{1}{\Delta t} \int_0^{\Delta t} a(\tau) d\tau \right]^{2.5} \quad (2.1)$$

where $a(\tau)$ is the head acceleration normalized with respect to gravity g and Δt is measurement duration which is often taken as $15ms$ to investigate head concussion injuries [57].

HIC has been used in robotics as a severity indicator for potential injury due to blunt impacts to a human head. Such collisions typically exhibits a high frequency behaviour above the controller bandwidth and thus are mainly influenced by the link dynamics, and for stiff robots also by the motor dynamics. [15] used HIC based safety requirement to identify dynamic constraints on a robot and then used the constraint information obtained to define a performance metric that allows a better trade-off between performance and safety. The effect of different robot parameters on HIC is analyzed and experimentally verified in [70]. This insightful work included experimental results with different robots to conclude that a robot of any arbitrary mass can not severely hurt a human head if measured according to HIC because of the low operating speed. In a subsequent overview publication, the authors applied a number of safety criteria while investigating the safety of a manipulator at a standard crash-test facility [69]. The authors conducted a meticulous safety analysis of the manipulator based on human biomechanics and were able to present quantitative experimental results using different safety metrics for head, neck and chest areas. For unconstrained blunt impacts the authors used HIC as a metric for severe head injury. While reviewing different topics in physical human-robot interaction, [163] noted the need for a new type of safety index in robotics other than HIC because the type of injury and operation speed in robotics

is different from that of the automotive industry where HIC is a standardized metric during crash tests.

Other metrics whose results are interpreted based on HIC were also reported in literature. [211] proposed a metric based on HIC known as Manipulator Safety Index (MSI) that is a function of the effective inertia of the manipulator. After identifying that safety of a manipulator is influenced mainly by the effective inertia of the robot, this index is used to compare effective inertia and hence safety of different manipulators under a constant impact velocity and interface stiffness. This metric was used to validate safety of a manipulator after design modifications in [168, 169]. [137] developed and investigated three danger indexes whose results were interpreted based on HIC. The work investigated force, distance and acceleration related danger indexes on a model to give quantitative measure of severity and likelihood of injury. The authors proposed a danger index that is a linear combination of the above qualities and takes into account speed, effective mass, stiffness and impact force.

2.2.2 Force based

The other category of safety metrics for contact injuries is the force based criteria which considers that excessive force is the cause of potential injuries and thus should be limited. Covering detailed analysis on force based criteria, authors in [82] used minimum impact force that can cause injury as a factor to define a unitless danger index to quantify safety strategies. The danger index α of a robot is defined as

$$\alpha = \frac{F}{F_c} \quad (2.2)$$

where F_c is the minimum critical force that can cause injury to a human and F is the possible impact force of the robot. It was shown that quantifying safety using this extendable metric was used to achieve safer design and improved control strategy. In the mechanical design aspect the index was used to relate safety and design modifications such as low mass, soft covering, joint compliance and surface friction or a combination of them.

[75] proposed three safety requirements essential in human robot interaction: ensure human robot coexistence, understandable and predictable motion by the robot and no injuries to the user. The author then defined a safety metric called impact potential based on the maximum impact force that a multi DOF robotic manipulator might exert during collision. For a set of possible impact surfaces on the robot P , the impact potential is given as

$$\pi = \sup_{p \in P} \pi_p \quad (2.3)$$

,where π_p is worst case impact forces at contact point p on the surface of the robot.

Due to the low HIC values observed even for heavier robots as a result of low collision velocity, [147] proposed to use minimum forces that cause damages to

different body parts as a safety metric. Since different body parts have different tolerance limits, the limit for neck injuries was chosen as a working criteria as it has the lowest value. A force based safety criteria was used by [37] to investigate safety of a pneumatic muscle actuated 2-DOF manipulator because HIC, according to the authors, does not provide an absolute measure of danger. While analyzing safety of a manipulator with respect to injuries at different parts of the body, [69] used maximum bending torque as neck injury metrics and verified safety for quasi-static constrained impacts at different body parts by using the maximum contact force as a metric whose allowed tolerance for different body parts is previously known.

2.2.3 Energy/power based

Different empirical fits were being suggested for the Wayne State data other than HIC approximations and one of them proposes reducing the power in equation (2.1) to 2 [135]. According to this approximation, the equation then becomes

$$f = \Delta t \cdot \underbrace{\left[\frac{1}{\Delta t} \int_0^{\Delta t} a(\tau) d\tau \right]}_{a_{ave}}^2 \quad (2.4)$$

$$f = \frac{\Delta V^2}{\Delta t} \quad (2.5)$$

where a_{ave} is the average acceleration and ΔV is the change in velocity of the head.

According to this expression, the injury on a human head acquires a physical meaning and is defined to be proportional to the rate of kinetic energy transferred during the collision. This observation was also stated in another power based injury evaluation of constrained organs called viscous criterion [44] where the injury was defined to be proportional to the rate of potential energy delivered to the body. Mathematically, the viscous criteria v_c is

$$v_c = \frac{\Delta X^2}{\Delta t} \quad (2.6)$$

where ΔX is the amount of compression on the organ and Δt is duration of the compression.

From the new interpretation of injury given in (2.5) and (2.6), a new power based head injury valuation metric known as Head Impact Power (HIP) was suggested in [135]. The metric was examined on head impact experiments using test dummies which reconstruct data specified in the mild traumatic brain injury (MTBI) database of concussion injuries on professional football players. It allows injury analysis of a head from an impact coming from all directions by considering both rotational and translational motion of the head during the experimental investigations. Afterwards, the MTBI-HIP risk curve is provided from a logistic plot of the probability of picking up a concussion injury versus the amount of power.

The risk curve enables the determination of the maximum amount of power that an adult human can sustain before developing a concussion and this maximum limit is

$$P_{max} = \begin{cases} 12KW & \text{for frontal impacts} \\ 10KW & \text{for non-frontal impacts} \end{cases} \quad (2.7)$$

The HIP is only used to analyze injuries of unclamped blunt collisions and can be combined with the viscous criterion to obtain a compete power based metric that can address injury levels of both collision types.

Uncontrolled extra energy was also suggested as cause of accidents in robots [153] and various experimental tests on the dynamic responses of human biomechanics during impact were performed to define energy based safety metrics that can be used in robotics. [201] and [126] identified the maximum allowed energy per volume before a possible cranial bone failure risk on adult and infant subjects respectively. The amount of energy that can cause fracture of neck bones and cause spinal injuries were determined in [205]. The energy tolerances for different injury types are

$$E_{max} = \begin{cases} 517J & \text{adult cranium bone failure} \\ 127J & \text{infant cranium bone failure} \\ 35J & \text{neck fracture} \end{cases} \quad (2.8)$$

It is apparent that, since the aforementioned energy based tolerance values are obtained from severe fracture injuries, they can not be directly used as acceptable safety threshold limits for domestic robots.

2.2.4 Other parameter based

Other safety metrics proposed for use in domestic robotics are based on factors such as pain tolerance, maximum stress and energy density limit. The human pain tolerance limit for clamping or sudden collisions was used as a metric for safe robot design by [177]. The pain tolerance limit of a human at different parts of the body was used to identify the admissible force during normal operations and a soft covering of the robot was designed based on this value. Strong correlation between the pain felt by a human and impact energy density was indicated from experimental investigation on collision of a robotic manipulator with a human [152].

[195] focused on skin injury to a human and provided a safety metric that evaluates the safety of a robot design based on its cover shape and material covering. By using Hertzian contact models to represent the impact, the proposed safety norm identifies safe design choices by evaluating the maximum stress on the skin that will occur during impact of a point on the robotic cover against a human body. Focusing on soft tissue injuries, [145] also developed a Hertz contact theory based collision model between a covered robot and a human head to analyze laceration and contusion injuries. Then by using tensile stress and energy density limits of the skin as a safety criteria, the authors proposed allowable elastic modulus and

thickness for a robot covering. Soft tissue injuries that might result from sharp edge contacts between robot operated tools and a human user were assessed using medical classifications in [71]. Instead of using using a safety metric to define the injury level observed, this experimental study defined a risk curve that directly relates the observed injury with the mass, velocity and geometry parameters of the operating robot.

2.3 Mechanical Design and Actuation

Safety in mechanical design and actuation deals with the crucial issue of ensuring inherent safety, i.e., safety even in the unlikely case of loss of the entire control system. To achieve inherent safety, robotic arms mounted on domestic robots are designed to be lightweight and compliant so as to mitigate any possible injury that may arise in case of uncontrolled collision with human. The presence of compliant behavior in the manipulator might result in unwanted oscillations during motion and compromise system performance. Hence, advanced controllers should be used to compensate the performance degradation in flexible robots [39] and enable acceptable trade off between safety and performance [15]. The most widely used performance metric in mechanical design of robotic manipulators is the payload-to-weight ratio which is defined as the ratio of maximum payload that the robot can manipulate to its standalone weight. Mechanical designs in domestic robot manipulators are aimed at achieving a higher payload-to-weight ratio while being able to perform tasks defined in their use case [76, 168].

The main safety based design rationale behind the light weight links in domestic robotics is reducing the impact force by lowering the kinetic energy of the link. Compliance between the actuator and the end effector is essential to decouple the actuator inertia and the link inertia, so that only the inertia of the lightweight link is felt during uncontrolled impact. The dynamic relationship between the desired decoupling behaviour, the maximum impact force and the mechanical properties of flexible manipulators was recently investigated in [68]. [70] indicated that even a moderate compliance achieved by using harmonic drives was able to yield required decoupling and further lowering of compliance reduces impact torque at the joint, thereby protecting the robot itself during collision. The compliance can be implemented as either virtual compliance by using control [160, 93, 76], passive compliance by inserting elastic elements at the joint actuation [200] or a combination of both in one manipulator as used in [165]. Though virtual compliant manipulators offer satisfactory performance for nominal operation, current investigations in compliant actuation are trying to exploit the wide range of compliance and faster dynamic response rate offered by passive compliance [194, 200].

The first approach to have a compliant robot, called Series Elastic Actuation (SEA), was done by inserting a passive compliant element between the joint and the actuator's gear train [197]. The authors presented a force controlled actuation with less danger to the environment and less reflected actuator inertia during im-

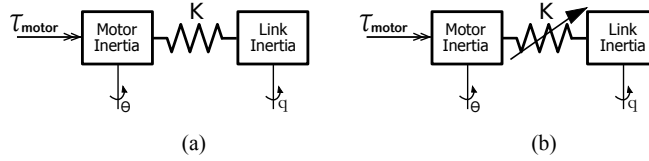


Figure 2.2: Schematics of (a) SEA and (b) VIA

pact. See Figure 2.2(a). A modified SEA actuation approach, variable impedance actuation (VIA), allows tuning of the compliance in the transmission for improved performance and collision safety [184, 15, 146]. This mechanism allows for adapting the mechanical impedance depending on the tasks, to yield a wide range of manipulation capabilities by the robot. See Figure 2.2(b). Various VIA designs have been proposed in literature, that differ in their range of motion and stiffness [199, 91, 192, 51]. Though the potential inherent safety of SEA and VIA comply with the prioritized risk reduction of mechanical design over control system as proposed in ISO 12100, the energy stored in the compliant element of VIA can lead to increased link speed and compromise safety as indicated in [63]. It should also be noted that, VIA design also incorporates damping of the compliant joints to avoid unnecessary vibrations during operation.

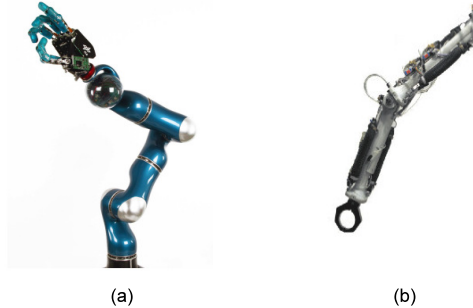


Figure 2.3: (a) DLR lightweight robot arm and hand [3] and (b) Stanford Safety Robot [168]

One of the earliest generation of manipulators designed for human interaction is the DLR lightweight robot with moderate joint compliance and suitable sensing and control capability [76]. See Figure 2.3(a). The manipulator was planned to perform human arm like activities and mimicked the kinematics and sensing capability of a human arm. The manipulator has an active compliance, made possible by a joint torque control and was able to have a payload-to-weight ratio of approximately 1:2. New generations of the DLR lightweight robot included advanced control system [4] and achieved a payload-to-weight ration of 1:1 whilst safety for interaction is evaluated by using HIC [3]. A new DLR hand arm system was also developed with the aim of matching its human equivalent in size, performance and weight [59].

The design uses a number of variable stiffness actuation designs and exploits the energy storing capability of compliant joints to perform highly dynamic tasks.

Another actuation scheme designed to fit in the human friendly robotics is distributed macro-mini actuation (DM2). This novel actuation mechanism introduces two parallel actuators that handle the high and low frequency torque requirements [210]. In the first prototype that uses this mechanism, the low frequency task manipulation torque actuation was handled by a larger electrical actuator at the base of the arm while high frequency disturbance rejection actions were performed by low inertia motors at the joints. Compliance is provided by using low reduction cable transmissions for the high frequency actuation and series elastic actuation for the low frequency actuation. A continued research by the research group introduced Stanford Human Safety Robot, S2 ρ , with the same distributed actuation concept but replaced the heavy electrical actuators with pneumatic muscles to have a hybrid actuation arm [168]. The authors reported an improved payload-to-weight ratio and control bandwidth while evaluating the safety requirements using Manipulator Safety Index (MSI). Further iterations on the S2 ρ were indicated to have an improved control, responsiveness and range of motion [169].

Another mechanical design relevant for safety of a robot is a passive gravity compensation shown in [187]. The mechanism which is common in machine design uses geometrical analysis and springs to balance the gravitational energy with a strain energy. Previously passive gravity compensation was made possible by using a counter mass that annuls the effect of gravity on the target manipulator. The spring based system has an advantage over the counter mass in that it avoids addition of inertia which is unnecessary in domestic robotics. An extended arm actuation mechanism that uses passive gravity compensation was presented in [202]. Together with a backdrivable transmission this design enhances safety and reduces the torque requirement at the joint actuators.

Though most of the discussion in this section focused on manipulators that can be used on autonomous domestic robots, the idea similarly applies to mechanical design of other robot parts such as trunk or mobile base. Aiming to emulate a natural reaction of human's waist to collision, authors in [121] designed a passive viscoelastic trunk with a passive movable base. Other mechanical design issues addresses with regards to safety include using a backdrivable transmission [85], eliminating pinch points by covering dangerous areas of the robot, analyzing flexibility of non-rigid links [163], adding force limiting devices [115] and placing a compliant cushion covering [177].

2.4 Controller Design

When it comes to controlling the robot to execute a planned motion and accomplish a task, most industrial robots use position controllers. This is because most robots perform position focused simple tasks such as spot welding, spray painting or pick and place operations in well known operating environment [36]. In tasks that

demand contact with an object during operations, industrial robots adopt force control techniques to regulate the amount of force applied by the robot during the interaction [209]. Later, based on operational force and position constraints imposed on a manipulator, a hybrid position/force controller was introduced that uses position control on some degree of freedom and force control for others [56, 40, 206]. In general, pure position controller exhibits an infinite stiffness characteristic working in a zero stiffness environment while pure force controller exhibits a zero stiffness characteristic working on a stiff environment.

For domestic robots that often operate in human present unstructured environment, pure position control is incomplete because if there is a contact with an obstacle, the robot is not expected to go through the obstacle. Similarly a pure force control is also inadequate as contact-less tasks and motions are difficult to implement. An alternative control technique essential in domestic robotics is interaction control scheme, which deals with regulating the dynamic behaviour of the manipulator as it is interacting with the environment [35, 176]. The core idea behind interaction control is that manipulation is done through energy exchange and that during the energetic interaction the robot and the environment influence each other in a bidirectional signal exchange. Thus by adjusting the dynamics of the robot, how it interacts with the environment during operation can be controlled.

One of the most widely used interaction control scheme is impedance control presented in [78]. Most operating environments of the robot such as mass to be moved or rigid obstacles in work space can be described as admittances which accept force inputs and output velocity during interaction. Hence for possible interactions in such environment, the manipulator should exhibit an impedance characteristic which can be regulated via impedance control. Consider a simplified 1-DOF robotic manipulator modeled as a mass m at position x which is to be moved to a desired position x_d , a simple physical controller that can achieve this is a spring connected between the desired virtual point and the mass. See Figure 2.4. To avoid continuous oscillation of the resulting mass-spring system and stabilize at equilibrium point a damper should be added to the system. The resulting controller is an impedance controller that can shape the dynamic behaviour of the system.

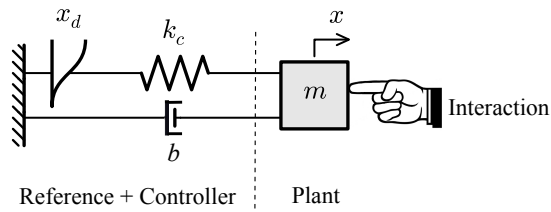


Figure 2.4: Impedance controlled system

The controller resembles a conventional PD controller and introduced a desirable compliance to the system. A number of impedance controller designs have

addressed issues such as robustness [30, 62], adding adaptive control techniques [100, 124], extension with learning approach [24], dynamics of flexible robot [4, 94], dexterous manipulation [14, 3, 32].

Another crucial requirement in controller design for domestic robots is ensuring asymptotic stability even at the presence of apparent uncertainties about the properties of operating environment [3]. To address this issue, different authors have applied passivity theory to design controllers commonly known as passivity based controllers [144, 167, 4]. Passive systems are class of dynamic systems whose total energy is less than or equal to the sum of its initial energy and any external energy supplied to it during interaction. Hence passivity based controller design ensures a bounded energy content and the system achieves equilibrium at its minimum energy state. Any energetic interconnection of two passive systems wont affect the passivity of the combined system. As a result an interconnection of a passivity based controller, a passive manipulator and a typical unstructured operating environment which is often passive results in an overall passive system whose Lyapunov stability is always guaranteed. Passive controller designs for domestic robot manipulators have been often addressed together with interaction control in a unified scheme to achieve a compliant, asymptotically stable and robust manipulator [4, 198, 208].

Safety aware control schemes that incorporate safety metrics in controller design were also proposed in literature. Focusing on collision risks to a human user, these controllers utilize a given safety metric to detect possible unsafe situations and use the controller to ensure acceptable safety levels defined in the metrics are achieved in order to avoid possible injuries. Using impact potential as a safety metric, [75] proposed an impact potential controller for a multiple DOF manipulator. In this hierarchical controller design approach, the resulting safety status of a high level motion controller torque output is evaluated according to the metric by a protective layer controller and clipped to an acceptable level in case of possible unsafe condition. By using energy levels that cause failure of the cranial and spinal bones as a safety criteria, authors in [113] propose an energy regulation control that modifies desired trajectory of the controller to limit overall energy of a manipulator. After analysing soft tissue injuries and their relation with robot parameters, [71] proposed a velocity shaping scheme that ensures possible sharp contact with a multiple DOF rigid robot wont result unacceptable injury to a human user.

Controller design can also increase post-collision safety by including collision detection and reaction strategy. By using model based analysis, authors in [123] defined energy based collision detection signal by using disturbance observer and identified a number of reaction strategies to both stiff and compliant robots.

2.5 Sensing, Perception and Motion Planning

In dealing with safety of a domestic robot that will share an environment with a human user it is necessary to be aware of its surrounding environment [214]. It is

important to classify the environment into different regions and devise appropriate safety strategy for different events in those regions. The National Institute of Standards and Technology (NIST) identified three safety regions for industrial robots depending on the distance from the robot [107]. They are the volume immediately around the robot covering a few centimeters above each surface of the robot, the area within the reach of the manipulator and the rest of the area inside the fenced barrier. This can be extended to domestic robotics by adding a fourth region where a human being is present and removing the idea of the barrier and considering the entire home environment as a safety region. See Figure 2.5. This qualitative information can be used as a safety criteria and it can also be easily quantified to define safety metrics such as sensor error while following a human moving at a certain velocity. The environment model constructed from sensor data should capture these regions as it is essential in motion planning and safety monitoring.

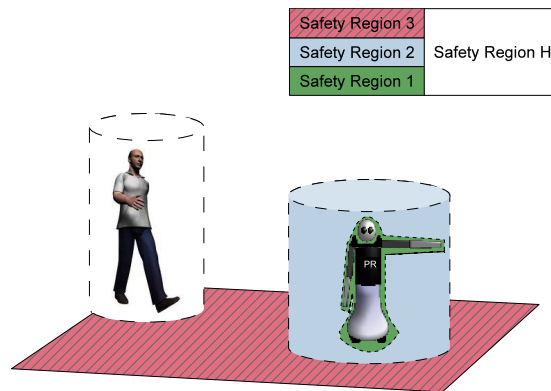


Figure 2.5: Safety regions recommended in domestic robotics

Understanding the operating workspace is made possible in robots by sensor data that contains the state of the robot and the environment. Some sensor outputs, such as positions or torques, can be used by the controller without further processing and other sensor outputs, such as images, are further processed before they are used, mostly in motion planning. A task in domestic robotics is often described by an action to be performed by the robot on the environment, for example pick and place tasks. Thus it is essential to represent sensor data in a task-oriented environment model, using a perception process [34]. These sensors can be mounted on the robot itself or the data can come from sensors mounted in the operating environment.

The complete data processing from the physical sensor level to the the environment model together with challenges in noise, digitization, communication, real-time requirements and computation power make sensing and perception a broad topic. Furthermore, the presence of uncertainty due to the changing human environment makes this one of the challenging problems in domestic robotics [101].

An autonomous domestic robot as an intelligent safe system should intrinsically

be able to handle uncertainty in the environment model [213]. In order to deal with this uncertainty, a domestic robot should be equipped with a range of sensors including proximity, force, tactile, vision, sound, temperature [163, 101]. Increasing the type and number of sensors gives redundancy to the system and yields an improved environment model, while at the same time it increases cost and complexity. Hence the number and type of sensors should be selected efficiently and then the information from these sensors has to be combined to generate unified world model with the four safety regions shown in Figure 2.5 [25]. This technique is known as multisensor data fusion [72].

The sensor fusion can be used in complimentary mode to combine information from sensors that cover different range of operation or redundancy mode where sensors have same range of operation. [38] identified three levels at which sensor fusion can take place, depending on the input and the stage of processing. They are data fusion, mostly done at lower level from similar sensor equipments, information fusion, performed at intermediate level processing and decision fusion, which combines decisions based on separate sensor data. See Figure 2.6.

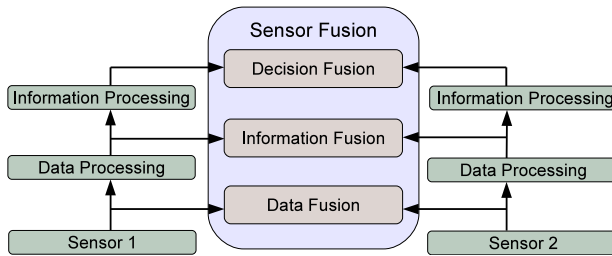


Figure 2.6: Different levels of processing in sensor fusion

Most sensor fusion applications in robotics are based on probabilistic methods [47]. These probabilistic methods are based on Bayesian probability rules for processing information by combining apriori and observation information. Practically, this can be implemented as Kalman filters, extended Kalman Filters [92, 156] or Monte Carlo methods. These probabilistic methods have three basic limitations namely; complexity, inconsistency and model precision [47]. In order to deal with the downsides of the above methods new implementation techniques were proposed that use interval calculus, fuzzy logic, neural networks and theory of evidence also known as Dempster-Shafer (D-S) methods [47]. A concise review on multi-sensor fusion is found in [47].

A dependable, efficient and dynamic human detection and tracking feature is an indispensable component that should be part of a domestic robot as it is considered as one of the most important protection mechanisms [58, 203]. It can be achieved with an increased performance from advanced sensor technology and by combining different sensors to obtain more informative and reliable data. Different authors indicated the importance of sensor fusion to increase safety in industrial applications by using one of the methods discussed above [98, 214, 48]. These works mostly

focused on a partially structured environment with a human presence and make use of intelligent environments which might not be implemented in an ordinary home environment. However, except few works like [96, 122], this issue of sensor fusion had little attention in the context of domestic robotics applications.

Motion planning is the task of finding a collision free path from start configuration to goal configuration while considering the dynamic and kinematic constraints of the robot. Though the general problem is presented in Cartesian space, most authors look for the solutions in the configuration space [117] while others opt to use cartesian space to compliment the configuration space solution [139]. The term path planning, often discussed together with motion planning, differs from the latter in that the computed path lacks time parameter. Because domestic robots are expected to operate in an environment where sudden movements and position changes are inevitable, motion planning schemes that react to environment changes should be used. Because such a reactive motion planning depends on system dynamics, and hence timing, motion planning is considered more relevant in safety than path planning [118].

Depending on the type of obstacles in the operating environment, motion planning problems as well as the algorithms can be classified as static or dynamic. The static algorithms define the basic problem of planning in a static environment while dynamic ones deal with a dynamic environment with moving obstacles. There are a number of static and dynamic planning algorithms reviewed in [95] and [102] respectively. A brief but insightful information regarding motion planning is given in [117] while in-depth discussion is found in [114, 116]. Given the geometrical description of the obstacle and a target configuration, the first task, also the biggest problem, in motion planning is mapping obstacles to the configuration space [139]. Then a collision free path is computed using a large scale global planner that is corroborated by real-time information based local planners [111].

The basic collision avoidance problem is one of the most important protection level considerations in safety of personal care robots [203]. Since this general problem is discussed in various literature it is left out of this review; further safety related advancements in the planning are presented. In the context of safety, with Murphy's law in mind, it is intuitive that collision avoidance alone does not suffice. Additional geometric as well as dynamic constraints should be placed on the conventional planning algorithm such as minimum distance from obstacle, maximum motion velocity in presence of human, etc. Techniques suggested in literature to include these safety features in motion planning are *potential based methods*, *cost function based methods* and *state based methods*.

One of the well known motion planning methods, the potential based method [104], tries to guide a robot through the gradient of an artificial potential field generated in such a way that the robot is attracted by the goal and repelled by obstacles. This planning algorithm is characterized by its advantages: low level control implementation, dynamic nature to handle change in environments and disadvantage: possibility of local minima. Other modifications were proposed that aim to solve this negative side of an impressive method [31]. Though not from

purely safety considerations, the method identifies a certain region of influence around the obstacles where the potential from that obstacle will be felt. Another potential based elastic strip framework for motion generation in human environments was described in [19]. After identification of a global candidate path with discrete representation of the trajectory, a workspace volume of collision free configuration space around that candidate path is computed to yield an elastic tunnel containing the path. The local reactive motion planning avoids obstacles by using an external potential to deform this elastic tunnel. By decomposition of the total torque in the joint space dynamics, this framework showed a motion behavior that can avoid dynamic obstacles, accomplish tasks and control the robot posture all at the same time.

Different motion planning algorithms that include cost functions with human safety considerations were proposed in literature. After expressing uncertainty about obstacle position in danger levels, a cost function based scheme that uses the defined danger level was introduced in [128]. The authors represented the danger level by a fractional potential obtained from distance between obstacles and the robot. The sum of the fractional potential map of each obstacle is summed to have the potential of the environment and hence danger level of the environment. Then path planning is done by an algorithm that minimizes a cost function dependent on this danger level. While this method was implemented for a 2D path planning scheme, it was suggested by the authors that it can be extended to multi-dimensional environments. But it remains unsuitable to use in domestic robotics as it lacks the ability to deal with dynamic environments. Another danger based motion planning was proposed by [111] which searches a configuration that minimizes a cost function generated by using a weighted combination of goal seeking, obstacle avoidance and danger criterion functions. The authors used a danger criteria which is a function of the robot inertia and relative distance between the robot and the user's center of mass. See Figure 2.7.

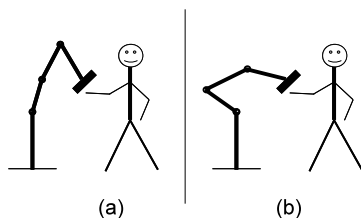


Figure 2.7: Posture (b) minimized risk to the user [111].

[171] introduced an elaborate motion planner for a mobile robot by using a cost function that combined safety, visibility and hidden zone costs. The authors considered human physical capability and state to define a posture based safety grid that can capture natural reaction such as a human being feeling more safe around a robot while standing up rather than sitting down. Then the safety criteria

includes cost function that depends on the human posture and distance between the robot and a human. Visibility cost attempts to capture the natural fact that a human feels comfortable if the robot is in sight. The hidden zone cost is an extension that handles surprise effects of a motion where a robot which was hidden behind an obstacle suddenly appears in sight of a user. An advanced planning for a manipulator was introduced in [112] that uses cumulative danger field as a safety cost criterion. The cumulative danger field $C\vec{D}F(\mathbf{r}, \mathbf{q}, \dot{\mathbf{q}})$ is a function of the robot's configuration \mathbf{q} and generalized velocity $\dot{\mathbf{q}}$; it defines danger associated with that configuration at a certain point \mathbf{r} in the robot workspace. In a bi-directional search to find a path from the goal to the start and the start to the goal, the algorithm attempts to find a complete path by searching a configuration that minimizes a heuristic function that includes a weighted cumulative danger field.

Focused on mobile robots moving in a simplified 2D environment, [29] reported an improved planning speed, safety and performance by using state based regions of inevitable collision (RIC). RIC is a collection of robot states that will lead to collision regardless of the control action; RICs should be avoided to ensure safety. RIC is computed from a set of reachable states and then a transition is made to a new state that is outside the RIC. The authors also introduced region of near collision and region of potential collision to further create classes of states and modify algorithms accordingly in each class. Even though this method guarantees safety in theory, it suffers from computational intensiveness and high dimensionality problems.

2.6 Conclusion

The previous sections of this chapter have presented different safety metrics and safety related issues in mechanical design & actuation, controller design and sensing, perception & motion planning. Even though safety of different subsystems which makeup the robot are treated separately in this chapter, it is important to note that safety also depends on the interaction between them. For example, a failure in the sensory unit is a risk not only in the sensing aspect but also has consequences in the motion planning or control. Such propagation of risks is essential and must be detailed in the risk assessment level of the safety analysis.

Continuous improvements in risk elimination or reduction designs are not possible without suitable safety metrics that can be used for validation. These metrics are needed not only for collision but also other feasible risks in domestic robotics. A number of collision focused safety metrics for domestic robots were discussed in this chapter and an experimental comparison of these metrics that follows a standardized testing procedure is essential to define a universally acceptable safety metrics for collision risks in domestic robotics. A groundwork towards a standardized safety evaluation of domestic robots for collision risks was performed at crash test facility in [64, 66].

Light weight and compliant manipulators are mechanical designs of choice in do-

mestic robotics. Ongoing researches on mechanical design and actuation to achieve better performing domestic robots should ensure that safety requirements are not violated as well. Control systems should also keep up with mechanical design and actuation advancements to guarantee stability and provide acceptable manipulation capability. A safe and reliable task accomplishment requires the robot to identify four safety regions in its environment. Such a requirement is achieved through perception which can yield a better result by combining different sensor data. This raises the basic problem of finding a trade off between the different kind of sensors that should be used for an acceptable performance and the complexity. Since accuracy and dependability of sensor data are improved with the statistical advantage of using multiple sensors, the enhancement of safety in domestic robotics by using multi-sensor fusion should be further exploited. Though motion planning is a widely undertaken research area, further attention should be given to include safety based design parameter in motion planning schemes for domestic robots. Though motion planning is a widely undertaken research area, further attention should be given to include safety based design parameter in motion planning schemes for domestic robots.

CHAPTER 3

PERFORMANCE BASED CONTROL DESIGN FOR HUMAN-FRIENDLY MANIPULATORS

“If you want to find the secrets of the universe, think in terms of energy, frequency and vibration.” Nikola Tesla

This chapter presents a general approach for a performance based design of an impedance controller for human-friendly robotic manipulators. Impedance control is a suitable control strategy for human friendly robots because the compliance it introduces improves safety and its passive nature guarantees asymptotic stability during interaction with unknown passive environments. In order to perform successful manipulation with an impedance controlled robot, a performance based analysis and design of the controller is essential. Insights from industrial manipulators suggest that accurate task accomplishment is made possible by their highly stiff behavior which is caused by the position control they possess. As a result, compliant manipulators that meet crucial safety requirements of domestic robots are susceptible to performance degradation. This work analyses this trade-off between safety and performance by using a frequency domain approach to relate system compliance and performance of manipulators. Then an impedance control design that yields a desired performance requirement is discussed, first for simple manipulator and later extended to address multiple DOF cases. The effectiveness of the proposed guideline is evaluated with simulation and experimental results.

This chapter is an extended version of the publication: T.S. Tadele, T.J.A de Vries and S. Stramigioli, “PID motion control tuning rules in a damping injection framework,” *2013 American Control Conference (ACC)*, Jun 2013

3.1 Introduction

Looking at their functionality, domestic robots can range from single purpose devices like autonomous vacuum cleaners to more complex mobile robots that can perform a multitude of activities using a manipulator. Robotic manipulators are mainly deployed in modern manufacturing industries to facilitate production lines and domestic robots can also adopt a manipulation capability to extend their services and perform many tasks. Due to differences in the type of task, design requirements and operational environments, the domestic and industrial manipulators exhibit opposing characteristics. Most industrial manipulators often use performance as a main design requirement while for domestic manipulators, safety requirement comes first in order. In general, industrial robots exhibit massive and stiff characteristic and domestic manipulators are lightweight and compliant.

As stated in sections 2.3 and 2.4, compliance can be introduced in human-friendly manipulators by using physical complaint springs placed at the joints or virtual compliance realized via an impedance controller. Even if safety is an essential design requirement for such manipulators, their competence as successful human assistants depends on their performance capabilities as well. For example, a poorly damped but compliant domestic manipulator can exhibit undesired oscillations that make a simple task of moving a liquid containing cup impossible. Hence it is crucial to analyze the performance of domestic robot manipulators and understand how the impedance controller design is related with performance requirements.

For domestic robot manipulators that mainly move objects, avoid obstacles and maintain boundaries during motion, an overall performance requirement can be defined in terms of the maximum deviation from its desired trajectory. Even though the performance measure is defined in terms of motion error, it is also applicable for tasks involving interaction and a table cleaning activity is used to elaborate this measure in the following section. The motion performance of the manipulator is directly related to its dynamic behavior which is in turn influenced by the impedance controller. As a result, the impedance controller can be designed in such way that a given performance requirement is met by the manipulator. In general, a manipulator with a highly compliant dynamic behavior can achieve an improved interaction safety for humans at the expense of a degrading motion tracking performance. Building on previous works that include frequency domain analysis for performance of impedance controlled systems [99, 149, 178], this chapter addresses the issue of performance with respect to the necessary damping and compliance behavior of the manipulator. It also proposes a general impedance controller design that demands no invertible matrix for implementation and can achieve a given performance requirement in the operational space.

This chapter is organized as follows. In section 3.2 background information and previous works related with passivity, cartesian impedance control, manipulator performance and addressing performance requirements in controller design are briefly presented. Then section 3.3 discusses a performance based impedance

controller design for a simplified 1-DOF manipulator to be followed by its multidimensional extension in section 3.4. Then section 3.5 presents simulation and experimental results before the main ideas are summarized with a conclusion in the final section.

3.2 Background Concepts

3.2.1 Passive Systems

One of the basic requirements in controller design is guaranteeing the stability of a system and in the case of human-friendly manipulators, the controller should deal with stability of the system even during interaction with an unknown environment. Different authors have proposed the use of passivity theory in controller design to ensure that the system possesses a bounded energy which can be used to guarantee Lyapunov stability and maintain the stability during interaction with unknown objects [3, 208, 143]. Passive systems are characterized by having a total energy which is less than or equal to the sum of its initial energy and any external energy supplied to it during interaction. That means passive systems have no inherent energy production and thus achieve equilibrium at the minimum energy state. Given a system with generalized energy $V(t)$ and which is interacting with the environment via power conjugate variables $u(t)$ and $y(t)$, it is a passive system if

$$V(t) - V(0) \leq \int_0^t y^T(\tau)u(\tau)d\tau \quad (3.1)$$

Another important concept in passivity theory is that energetic interconnection of passive systems results in another passive system. Accordingly, a controller design which ensures passivity of the interconnected controller plus plant system can guarantee system stability during interaction with a typically passive operating environment. Such a design approach where the interconnection between the controller and the plant results in a passive system is known as passivity based control [167].

3.2.2 Cartesian Impedance Control

Multidimensional extension of the simple impedance controller introduced in section 2.4 can be used for multi-link robotic manipulators. For rigid multi-DOF serial manipulators which are considered in the scope of this thesis, their Lagrangian dynamic equation is given as

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \tau_{tot} \quad (3.2)$$

where $M(q)$ is the inertia matrix, $C(q, \dot{q})$ represents the Coriolis and centrifugal terms, $G(q)$ is the gravitational forces and τ_{tot} is the equivalent of all joint forces on the manipulator.

While the system dynamics equation and the actuation torque are defined in the joint space, a cartesian impedance controller is described in the operational space to successfully accomplish tasks. In general, the controller objective for multi-DOF manipulators is to achieve a required cartesian impedance while moving the end-effector of the manipulator towards a desired configuration. The configuration of the end-effector could be conveniently expressed by using a body-fixed reference frame with explicit homogeneous matrix H that belongs to a Special Euclidean Lie group $SE(3)$ defined as

$$SE(3) = \left\{ \begin{pmatrix} R & p \\ 0 & 1 \end{pmatrix} : R \in SO(3), p \in \mathbb{R}^3 \right\} \quad (3.3)$$

where p describes the position and R is a rotation matrix that represents the orientation of the body. The matrix R itself belongs to a Special Orthonormal Lie group $SO(3)$ defined as

$$SO(3) = \{ R \in \mathbb{R}^{3 \times 3} : R^{-1} = R^T, \det R = 1 \} \quad (3.4)$$

The Lie algebra $se(3)$ associated with the group $SE(3)$ consists of twists that geometrically describe the velocity of rigid bodies in a coordinate-free way. The dual vector space of linear operators from $se(3)$ to \mathbb{R} comprises wrench elements that describe forces acting on the rigid body.

So, given two homogeneous matrices H_t^0 and H_v^0 which describe the current and desired configurations of a manipulator's end-effector, the cartesian impedance controller is physically described as a multidimensional spring with symmetric stiffness matrix $K \in \mathbb{R}^{6 \times 6}$ that attempts to co-align the configurations. In order to achieve a satisfactory dynamic behavior and guarantee a robust asymptotic stability, damping is added to the system. This damping can be injected either in the joint space via a damper b_n on each DOF or in the Cartesian space by using a multidimensional damper matrix $B \in \mathbb{R}^{6 \times 6}$. See Figure 3.1.

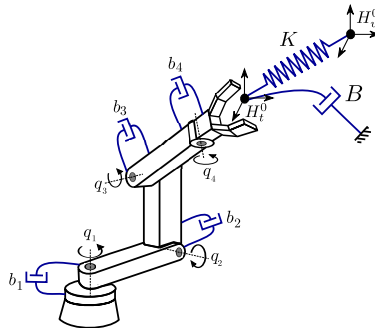


Figure 3.1: Cartesian impedance control of a manipulator: compliance added via a spatial spring defined by K and damping is introduced either via a spatial damper B or joint space dampers given by b_n .

The wrench W_k^t applied on the manipulator due to the spatial geometric spring connected is given as

$$W_k^t = \begin{pmatrix} m_k^t \\ f_k^t \end{pmatrix} = \begin{pmatrix} K_o & K_c \\ K_c^T & K_t \end{pmatrix} \begin{pmatrix} \delta\theta_t^v \\ \delta p_t^v \end{pmatrix} \quad (3.5)$$

where $\delta T = [(\delta\theta_t^v)^T (\delta p_t^v)^T]^T$ is an infinitesimal twist in vector form and K_t , K_o and K_c are the symmetric translational, rotational and coupling stiffness matrices representing the spatial compliance.

Extension of this infinitesimal case is necessary to compute the elastic wrench due to a spatial spring and this extension should ensure that the wrench output emulates a physical spring with similar stiffness characteristics [190]. Given a virtual spatial spring connected between the current and desired end-effector configurations, the translational, rotational and coupling stiffness matrices are used to define a respective co-stiffness matrices G_t , G_o and G_c as

$$G_x = \frac{1}{2} \text{tr}(K_x)I - K_x \quad (3.6)$$

where $\text{tr}()$ is the tensor trace operator. The generalized wrench exerted by the spring is a function of the relative configuration H_t^d ,

$$H_t^v = (H_v^0)^{-1} \cdot H_t^0 = \begin{pmatrix} R_t^v & p_t^v \\ 0 & 1 \end{pmatrix} \quad (3.7)$$

and the wrench $W_k^t = [m_k^t f_k^t]$ exerted on the manipulator due to the spring is expressed in the coordinates of the end-effector frame as [176],

$$\tilde{m}_k^t = -2as(G_o R_t^v) - as(G_t R_v^t \tilde{p}_t^v \tilde{p}_t^v R_t^v) - 2as(G_c \tilde{p}_t^v R_t^v) \quad (3.8)$$

$$\tilde{f}_k^t = -R_v^t as(G_t \tilde{p}_t^v) R_t^v - as(G_t R_v^t \tilde{p}_t^v R_t^v) - 2as(G_c R_t^v) \quad (3.9)$$

where $as()$ is an operator that gives the skew-symmetric part of a square matrix.

If a spatial damping is used, the wrench W_d^t felt at the end-effector of the manipulator due to the damper can be computed similarly [54] and the combined end-effector wrench W^t expressed in the reference frame of the end-effector itself is given as,

$$W^t = W_k^t + W_d^t \quad (3.10)$$

After coordinate transformation of the wrench to an inertial reference frame Ψ_0 , the duality nature of force and motion is used to compute the joint torques τ that can emulate the desired end-effector wrench on the manipulator.

$$(W^0)^T = Ad_{H_0^t}^T (W^t)^T \quad (3.11)$$

$$\tau = J^T(q)W^0 \quad (3.12)$$

where $Ad()$ is Adjoint of the homogeneous matrix.

The physical interpretation of the controller is also preserved in the Cartesian impedance control and this in turn allows the analysis of the controller as a dynamic system that can influence the plant towards a desired behavior [142]. Such a methodology expands the controller design technique beyond the classical signal based design and has advantages such as granting an insightful view of the system, simplifying tuning procedures and allowing system stability analysis by using the total energy as a Lyapunov function. Furthermore, the controller design avoids the common inverse kinematics problem of identifying joint motion requirements from cartesian space task definition. The dynamics of the manipulator can be further shaped by adding gravity and friction compensation terms in the joint torques.

$$\tau = J^T(q)W^0 + \hat{C}(q, \dot{q})\dot{q} + \hat{G}(q) \quad (3.13)$$

where $\hat{C}(q, \dot{q})\dot{q}$ and $\hat{G}(q)$ are compensation terms for the Coriolis, centrifugal and gravitational forces.

To accurately perform tasks which are often defined in cartesian space, the dynamic behavior of robotic manipulators in this operational space should be analyzed [105]. After introducing impedance control concept for manipulators, [78] addressed cartesian space dynamics of manipulators by using a model based controller design to modify the nonlinear inertia of the manipulator to a simple diagonal operational space inertia matrix I_m that interacts with the cartesian stiffness and damping defined in the controller. See Figure 3.2. The control design uses a computed torque approach to emulate the motion behavior of a diagonal inertia I_m on the manipulator by converting the cartesian space acceleration of the diagonal inertia to its joint space counterpart and compensating the gravitational, Coriolis and centrifugal forces of the manipulator. The control law then becomes,

$$\tau = M(q) (J^{-1}(q)I_m^{-1} (W^0 - N(q, \dot{q}))) + \hat{C}(q, \dot{q})\dot{q} + \hat{G}(q) \quad (3.14)$$

where $J(q)$ is Jacobian of the manipulator, I_m is the simplified diagonal inertia, W^0 is the virtual force defined in eq (3.11) and $N(q, \dot{q})$ is an intermediary term due to the acceleration transformation.

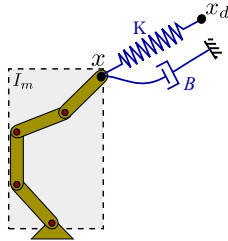


Figure 3.2: Cartesian impedance control of a manipulator with masked diagonal inertia I_m .

Another closely related approach tried to solve this problem by using the computed torque approach after redefining the manipulator dynamics in the operational

space. The dynamic motion equation for a manipulator in the operational space is given as [105]

$$\Lambda(x)\ddot{x} + \mu(x, \dot{x}) + p(x) = F_{tot} \quad (3.15)$$

where x describes the position and orientation of the end-effector, $\Lambda(x)$ is the inertia matrix, $\mu(x, \dot{x})$ represents the Coriolis and centrifugal forces, $p(x)$ is the gravitational forces and F_{tot} is the equivalent of all operational space forces on the manipulator. The operational space inertia matrix, obtained by equating the operational and joint space kinetic energies, is

$$\Lambda(x) = (J(q)M^{-1}(q)J^T(q))^{-1} \quad (3.16)$$

Then the end-effector motion becomes similar to that of an inertia I_m by selecting the acceleration term \ddot{x} of eqn (3.15) as [106],

$$\ddot{x} = I_m^{-1}W^0 \quad (3.17)$$

where W^0 is the force due to the cartesian stiffness and damping defined in eq (3.11). Finally the joint torques that compensate the gravity, Coriolis and centrifugal forces and that gives a desired end-effector motion equivalent to the inertia I_m is given as

$$\tau = J^T(q) (\Lambda(x)I_m^{-1}W^0 + \hat{\mu}(x, \dot{x}) + \hat{p}(x)) \quad (3.18)$$

where $\hat{\mu}(x, \dot{x})$ and $\hat{p}(x)$ are compensation terms based on estimates of Coriolis, centrifugal and gravitational forces in the operational space dynamics.

Among the cartesian impedance control laws given in equations (3.13), (3.14) and (3.18), the latter two can achieve a desired task space dynamics defined by the inertia I_m , stiffness K and damping B . But it is also important to realize that they have two clear drawbacks. The requirement of an invertible Jacobian matrix in (3.14) brings back another inverse kinematics problem which the impedance controller design attempted to eliminate in the first place. A similar need for invertible matrices during the computation of the cartesian space dynamics in the controller design given by (3.18) also makes it difficult to be a viable generalized solution to deal with operational space dynamics of a manipulator. Furthermore, the use of model based computed torque approach in both controller designs could result in a non passive behavior considering it is not a control by interconnection of a passively equivalent controller.

3.2.3 Manipulation and Performance in Impedance Control

Consider a typical table cleaning activity that is to be performed by a cartesian impedance controlled robotic manipulator, then the task can be accomplished by following a desired configuration which first brings the end-effector over the table and then moves towards under the table. Under this condition, the end-effector rests on top of the table and exerts a force against the surface due to the spatial stiffness that is pulling the end-effector towards the desired configuration under

the table. See Figure 3.3. Further motion of the desired configuration allows the end-effector to slide along the surface and perform the cleaning task. Then, a successful cleaning task can be described as maintaining appropriate contact force and following the motion pattern of the desired configuration without sliding off the table surface.

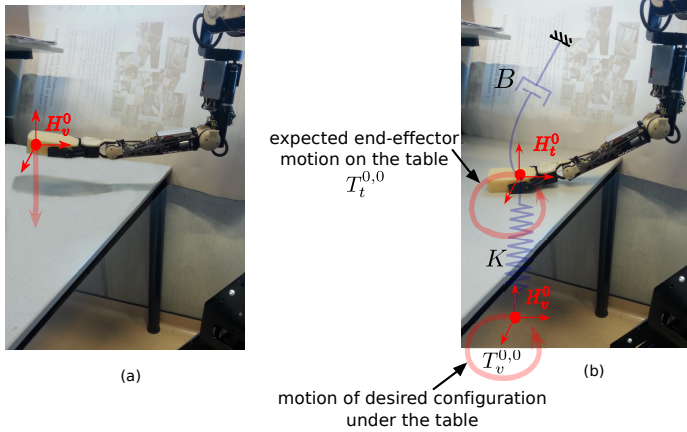


Figure 3.3: A robotic manipulator cleaning a table using cartesian impedance control: (a) The end-effector is brought to the top of the table before the desired configuration moves towards under the table. (b) Matrices K and B define the cartesian impedance as contact is established with the table and desired configuration H_v^0 moves in a circular pattern.

The effectiveness of the manipulator in applying a desired contact force and managing the motion error in the task space is affected by its cartesian impedance behavior. In order to analyze the success of the manipulation task against these two performance indices, their relation with the imposed cartesian impedance has to be properly investigated. The relationship between the desired cartesian impedance and the wrench exerted by the manipulator is well established and is given in equations (3.10) and (3.11). Additional investigation into the motion performance of the manipulator against a given cartesian impedance completes the performance analysis of a cartesian impedance controlled manipulator. The motion performance can be conveniently defined in terms of the maximum allowed motion error of the manipulator's end-effector while tracking the trajectory of the desired configuration.

It should be noted that the choice of motion error should not overshadow the user of impedance control over a standard position control. The advantages of impedance control for a human-friendly manipulator are certain and the motion performance analysis is focused on identifying the relationship between the cartesian impedance and the inevitable trajectory tracking error. In the table cleaning task for example, if a highly compliant cartesian impedance is selected, the motion error can increase and result in the end-effector moving beyond the edge of the table. The desired configuration will pull the end-effector even further under the

table and cause unwanted collisions in the environment. The common observation is that the higher performance with low motion error is achieved by a stiff cartesian impedance and increased safety with higher motion error is observed by compliant design. The analysis of cartesian impedance and motion performance determines possible performance losses due to compliant manipulation.

3.2.4 Controller Design and Performance Analysis in Frequency Domain

Frequency domain techniques have been used as an alternative to the time domain methods for analysis and design of control system for linear systems. In addition to the availability of stability analysis methods, frequency domain description of real world phenomena such as performance, vibration, bandwidth and noise made the frequency domain approach preferable in dealing with practical applications. The approach treats a controller as a lead-lag compensator that can influence the plant to achieve an acceptable stability margin as well as desired performance requirements [193, 188, 178]. Frequency domain approach has also been adopted for compliant motion analysis of a manipulator under given performance specifications [99].

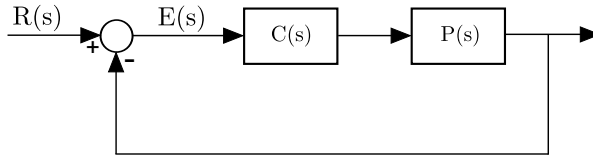


Figure 3.4: Standard feedback control system.

Given a linear closed loop system shown in Figure 3.4, system stability requirements of the classical Nyquist criterion requires the controller design to ensure acceptable phase and gain margins on the Bode plot of the open loop transfer function $P(s)C(s)$. For a simplified manipulator modeled as a moving mass, its Bode plot exhibits a decreasing magnitude with $-40dB$ slope and a constant $-\pi$ phase across the whole frequency spectrum. The controller should possess a phase-lead behavior to achieve a phase margin away from $-\pi$ at the crossover frequency and the impedance controller also satisfies this requirement.

The frequency domain approach can also handle transient and steady state performance analysis of a system. For typical robotic applications where moving objects to a desired position is an important requirement for a controller, its performance requirement can be defined in terms of the motion error $E(s)$

$$E(s) = \frac{1}{1 + P(s)C(s)} \cdot R(s) \quad (3.19)$$

Thus, controller $C(s)$ can be designed with the maximum allowed motion error as a performance requirement. The additional freedom of choice on the dynamics of

the reference motion $R(s)$ also aids the designer in realizing a desired error behavior. Since motion tracking performance for manipulation activities is a typically low frequency phenomenon, the maximum allowed motion error $E(s)_{max}$ can be defined as

$$E(s)_{max} = \max\{\lim_{s \rightarrow 0} E(s)\} \quad (3.20)$$

Steady state error can also be investigated in the frequency domain by using the final value theorem of the Laplace transform as follows,

$$E(s)_{ss} = \lim_{s \rightarrow 0} s \cdot E(s) \quad (3.21)$$

3.3 Performance Based Impedance Control for 1 DOF Manipulators

The impedance controller implementation chosen here for a simplified robotic manipulator is the damping injection framework that uses a physically interpretable design to circumvent the need for velocity measurements [175]. The damping injection framework introduces a virtual mass m_c and a bridging spring k_c between this virtual mass and the plant in addition to the basic impedance control design. See Figure 3.5.

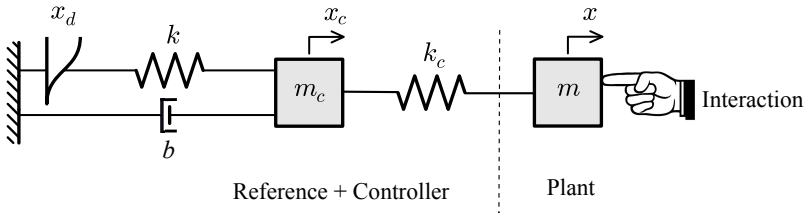


Figure 3.5: Damping injection framework.

If a very stiff bridging spring ($k_c \gg k$) and a small virtual controller mass ($m_c \ll m$) are chosen in the design, the motion of the plant mass can be assumed to be the same as the controller virtual mass. Consequently, a desired impedance and damping on the plant can be applied via the virtual mass which is stiffly attached to it. This implementation only demands position measurement of the plant and the damping effect is computed as a function of the controller mass velocity whose value is known as it is part of the controller's state. Furthermore, this physically interpretable controller implementation of the damping injection framework is also passive as it is an interconnection of passive mass, spring and damper elements.

In order to analyse the performance of an impedance controlled simple manipulator using the frequency domain approach presented in section 3.2.4, the system

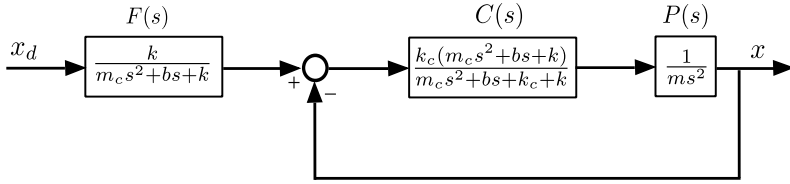


Figure 3.6: Block diagram representation of damping injection framework.

is first represented in a block diagram shown in Figure 3.6. The block diagram indicates that a damping injection framework constitutes a complex phase-lead compensator $C(s)$ and a setpoint pre-filter $F(s)$. Looking at Figure 3.7, it can be seen that the damping injection controller has a phase-lead frequency response that can be adjusted to attain a desired phase lead at the crossover frequency of the system. The frequency which gives the maximum phase lead for the system can be obtained by solving the equation

$$\frac{\partial}{\partial \omega} \angle C(j\omega) = 0 \quad (3.22)$$

By using trigonometric identities, the phase angle $\angle C(j\omega)$ can be given as:

$$\angle C(j\omega) = \tan^{-1} \left(\frac{b k_c \omega}{m_c^2 \omega^4 + b^2 - 2 k m_c - k_c m_c \omega^2 + k k_c + k^2} \right) \quad (3.23)$$

Introducing a scaling parameter A and damping ratio ζ as follows,

$$k_c = A k; \quad m_c = \frac{m}{A}; \quad b = 2 \zeta \sqrt{k m} \quad (3.24)$$

the maximum phase lead frequency ω_m can be defined using (3.22) and (3.23) as:

$$\omega_m = \sqrt{B} \sqrt{\frac{k}{m}} \quad (3.25)$$

where

$$B = \frac{A^2}{6} \left(\left(1 + \left(\frac{2}{A} \right) - 4 \zeta^2 \right) + \sqrt{\frac{12A + 12}{A^2} + \left(1 + \frac{2}{A} - 4 \zeta^2 \right)^2} \right) \quad (3.26)$$

By replacing variables from (3.24), (3.25) and (3.26) into (3.23), the maximum phase lead ϕ_{max} that can be obtained from the controller can be expressed as a function of design parameters A and ζ .

$$\phi_{max} = \tan^{-1} \left(\frac{2 \zeta A \sqrt{B}}{\frac{B^2}{A^2} + \frac{2B}{A} + 4B \zeta^2 + A - B + 1} \right) \quad (3.27)$$

The controller design starts with choosing a desired damping behavior by selecting appropriate value for damping ratio ζ . Oscillations can be avoided and a well damped behavior can be achieved for a the damping ratio in the range of $\zeta = 0.7 \dots 1$. Then the desired maximum phase lead ϕ_{max} in the controller is used to compute the scaling parameter A . While any positive value of A yields a phase-lead behavior that can guarantee asymptotic stability, higher values will result in an increased phase margin, and thus more robust system. However, it should be selected carefully because higher choice of A results an increased gain in the noise prone high frequency region. See the bode plot Figure 3.7. Thus is it recommended to select a lower value of A that yields an acceptable phase lead of at least 45° . The maximum phase lead ϕ_{max} may not be achieved exactly at the open loop crossover frequency of the system, the frequency at which $\|C(s) \cdot P(s)\| = 1$, but the phase lead at the frequency will be sufficiently close to ϕ_{max} in this approach.

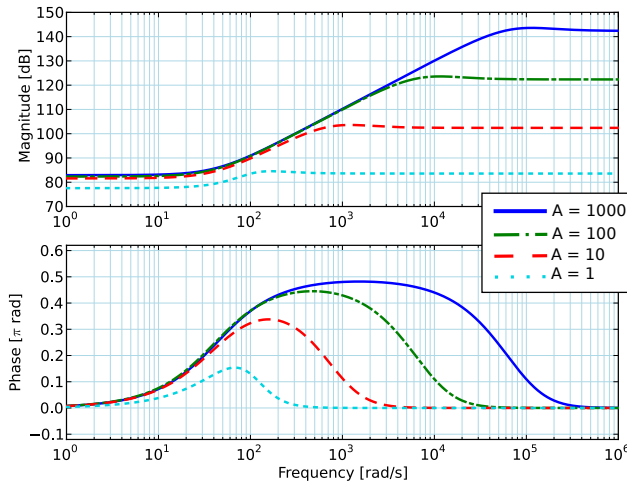


Figure 3.7: Bode plot of $C(s)$ for different values of A .

Once acceptable stability margins are established, performance requirement given in terms of maximum allowed motion error can be added to the controller design. For a damping injection injection framework shown on Figure 3.6, the motion error $E(s)$ is given by:

$$E(s) = x_d - x = x_d \cdot \left(1 - \frac{FPC}{1 + PC} \right) \quad (3.28)$$

Substituting system equations, the maximum motion error then becomes

$$E_{max}(s) \approx 2\zeta \sqrt{\frac{m}{k}} \cdot (sx_d)_{max} \quad (3.29)$$

$$e_{max} \approx 2\zeta \sqrt{\frac{m}{k}} \cdot \dot{x}_{d_{max}} \quad (3.30)$$

Using (3.25), the desired maximum phase frequency ω_m can be obtained as follows:

$$\omega_m = \frac{2\zeta\sqrt{B}}{e_{max}} \cdot \dot{x}_{d_{max}} \quad (3.31)$$

Finally with the scaling parameter A obtained from relative stability requirements and the maximum phase frequency ω_m identified from the performance requirement, all the controller parameters can be determined using eq (3.24) and eq (3.25).

Controller Design Procedure for 1 DOF Manipulator

To summarize the performance based impedance controller design method using damping injection framework,

- i Chose a desired damping behavior ζ and a design parameter A that yields an acceptable maximum phase lead in (3.27). The rule of thumb on the choice for damping ration is $\zeta = 0.7 - 1$ and it is preferable to select a phase lead value greater than $\frac{\pi}{4}$.
- ii Compute intermediate parameter B for the chosen scaling parameter A from (3.26)
- iii Use the maximum velocity $\dot{x}_{d_{max}}$ of the required motion profile and maximum allowed motion error e_{max} to determine maximum phase lead frequency ω_m from (3.31)
- iv Calculate desired interaction stiffness k using plant mass m in (3.25)
- v Compute the other parameters k_c , b and m_c from (3.24) and implement the controller.

3.4 Extension to Multi-DOF Manipulators

As stated previously, analysing the dynamic performance of a manipulator in the operational space is of paramount importance to successfully accomplish manipulation tasks by robots. Methods to address this issue center around defining a diagonal inertia that can mask the nonlinear plant dynamics and choosing suitable stiffness and damping matrices to achieve desired motion behavior by the manipulator. Choosing diagonal stiffness and damping matrices K and B further simplifies the system analysis by decoupling the motion of this multidimensional system.

Before addressing the control design for multi-DOF manipulators, let us evaluate performance requirements and the necessary cartesian space impedance behavior for a uniform, multidimensional and diagonal inertia. The result is then used to address the design of a generalized performance based cartesian impedance controller which is free from invertible matrix requirements.

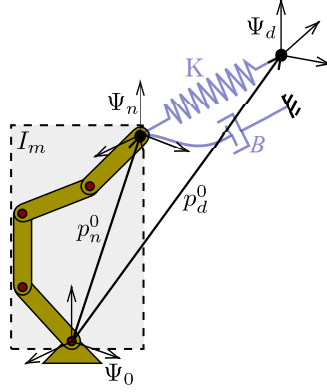


Figure 3.8: Masking nonlinear inertial of manipulator with diagonal inertia I_m .

For a diagonal inertia $I_m = m \cdot I^{6 \times 6}$ whose current configuration represented by homogeneous matrix H_n^0 and a desired configuration H_d^0 , the translational force component of the elastic wrench due to a spatial spring with diagonal stiffness matrix $K = \text{diag}([K_o, K_t])$, where $K_t = k_t I^{3 \times 3}$, is calculated using (3.9) and (3.11) as

$$f^0 = k_t(p_d^0 - p_n^0) = k_t p_d^{0,n} \quad (3.32)$$

where k_t is the translational stiffness constant, p_d^0 is the position of the desired configuration, p_n^0 is the position of the current configuration and $p_d^{0,n}$ represents the position error all expressed in the inertial frame Ψ_0 . See Figure 3.8.

If a diagonal damping matrix is also selected as $B = \text{diag}([B_o, B_t])$ where $B_t = b_t I^{3 \times 3}$, the equation of motion for the diagonal inertia I_m is decoupled in each degree of freedom. The x,y,z component of the motion error $p_d^{0,n}$ can be represented in Laplace domain as a function of inertia, stiffness and damping parameters m , k_t and b_t as

$$E(s)_i = \frac{ms + b_t}{k_t} v_{n_i}^{0,0}, \quad i \in x, y, z \quad (3.33)$$

where $E(s)_i$ represent the motion error in each degree of freedom and $v_{n_i}^{0,0}$ is the velocity component in the twist of the diagonal inertia I_m with respect to inertial reference frame Ψ_0 written in frame Ψ_0 .

Thus, the low frequency component of the motion error which defines the performance of the system is defined in each degree of freedom,

$$e_i \approx \frac{b_t}{k_t} v_{n_i}^{0,0}, \quad i \in x, y, z \quad (3.34)$$

Using similarity of parameters in each translational degree of freedom, the magnitude of the maximum absolute motion error e_{max} is given as,

$$e_{max} \approx \frac{b_t}{k_t} v_{n_{max}}^{0,0} \quad (3.35)$$

, where $v_{n_{max}}^{0,0}$ is the maximum velocity of the end-effector.

If the damping parameter is defined as a function of a damping ratio ζ and other parameters as $b_t = 2\zeta\sqrt{k_t m}$, then the stiffness parameter k_t that satisfies acceptable absolute motion error e_{max} is given as

$$k_t = \frac{4m\zeta^2}{e_{max}^2} \cdot (v_{n_{max}}^{0,0})^2 \quad (3.36)$$

Now that the relationship between the cartesian impedance and desired performance requirement is defined for a simplified diagonal inertia matrix, the next task is to extend the method towards a generalized approach that can be used for a nonlinear manipulator dynamics. The inconvenience due to the invertible matrix requirements of other approaches should be avoided in the proposed solution.

If a compensation backed cartesian impedance control law given in (3.13) is used, the controller should achieve the desired performance against the non-linear and configuration dependent operational space inertia. To achieve this, we propose the worst-case design approach of mechatronic systems where a controller is designed to achieve a desired maximum allowed motion error on the heaviest possible inertia. This means, when the controller encounters an inertia lower than the maximum value used in the design, the motion error will also be less than the maximum allowed value there by resulting in a performance within the tolerance limits. In manipulator control, an upper bound on the dominant operational space inertia can be used to define appropriate cartesian impedance for the manipulator.

In the dynamics of rigid mechanisms, the inertia matrix is a quadratic form in the Lie algebra $se(3)$ and it is a second order tensor defined as a multi-linear operator \bar{I} of the form [176]

$$\langle, \rangle_{\bar{I}} : se(3) \times se(3) \rightarrow \mathbb{R} \quad (3.37)$$

Physically this means inertia matrices define the energy associated with a given twist and is always a positive definite matrix. To identify the upper bound on the manipulator inertia matrix for our worst case design approach the following ordering definition is used.

Definition 1. Let A and B be any positive definite symmetric matrices, then $A > B$ if and only if $v^T A v > v^T B v$ for all non zero vectors v . This is called Löwner ordering.

This ordering can be physically interpreted as, if we compare two inertial matrices, the inertia which gives the higher energy for a given twist vector is greater. Similarly, a generalized inertia ellipsoid defined as a quadratic surface of the inertia tensor can also be used geometrically represent and compare inertia matrices [7].

As a result, given an operational space inertia $\Lambda(x)$ defined in (3.16), an upper bound diagonal inertia matrix I_m is defined by the condition $I_m > \Lambda(x)$ and this condition is true if and only if $I_m - \Lambda(x)$ is positive definite. If we use the kinetic co-energy as a comparison term, then the above mentioned inequality holds if and only if

$$\frac{1}{2} (T_n^{0,0})^T I_m T_n^{0,0} > \frac{1}{2} (T_n^{0,0})^T \Lambda(x) T_n^{0,0} \quad (3.38)$$

where $T_n^{0,0}$ is the end-effector twist.

The kinetic co-energy on the right side of the inequality in (3.38) can be rewritten in the joint space formulation and the upper bound cartesian space matrix I_m can be computed setting

$$\lambda \cdot \frac{1}{2} (T_n^{0,0})^T I_p T_n^{0,0} > \frac{1}{2} \dot{q}^T M(q) \dot{q} \quad (3.39)$$

where $I_m = \lambda I_p$ and I_p is a user defined preliminary diagonal inertia matrix that will be scaled to compute the worst case end-effector inertia.

Hence, once the end-effector twist $T_n^{0,0}$ and the inertia matrix $M(q)$ are calculated from joint states q and \dot{q} without any invertible matrix requirements, the scaling parameter λ that satisfies the inequality can be selected to define the upper bound inertia I_m . While the positive definiteness of the inertia matrix I_m and the inequality in (3.39) put a lower limit on parameter λ , it should be chosen to satisfy the inequality modestly in order to avoid unnecessarily stiff behavior that will be caused by higher inertia choice.

In summary, a desired performance requirement given in terms of maximum motion error can be achieved on a cartesian impedance controlled human-friendly manipulator by using a decoupled system with diagonal cartesian space impedance matrices and a diagonal upper bound of the operational space inertia. One important point to note here is that, the configuration dependent inertia of the manipulator results in a dynamic upper bound inertia matrix I_m , which in turn demands time varying controller parameters if the desired performance requirements are to be met through out the manipulator's operation. The pointwise linear time invariant method used for performance analysis defines a time variant controller to handle the nonlinear manipulator dynamics.

3.4.1 Performance based passive controller design

The proposed impedance controller design for multi-DOF manipulator demands variable stiffness and damping matrices to handle the time-varying inertia matrix of the manipulator and maintain the desired performance requirement. A straightforward implementation of this time-varying controller design contradicts with energetic consistency of interaction controller design. That is, without no external force, energetic interaction between the spring and the manipulator dictates that energy gain at the spring must be achieved at the expense of an energy loss at the plant. Varying the stiffness behaviour of the virtual controller spring violates this observation and allows internal energy production resulting in the loss of passivity of the overall system.

To address this issue and maintain the overall passivity of the system, an energy tank based controller design approach is used to implement a variable impedance controller. In the tank based implementation scheme, the controller is designed as a power flow modulator between an energy storage tank and a plant. See Figure 3.9. For an n DOF manipulator this physically interpretable controller consists

of n energy storage tanks $CS_1 \dots CS_n$ which behave like springs with a stiffness value of 1, transmissions $MT_1 \dots MT_n$ with transmission ratio $u = [u_1 \dots u_n] \in \mathbb{R}^n$ and a multiport computational unit CU . The computational unit calculates the transmission ratio vector u which determines how power flows between the storage elements and the plant. The complete system has bounded energy and is passive by design since it consists of energy transferring transformation and intrinsically passive mass and spring elements.

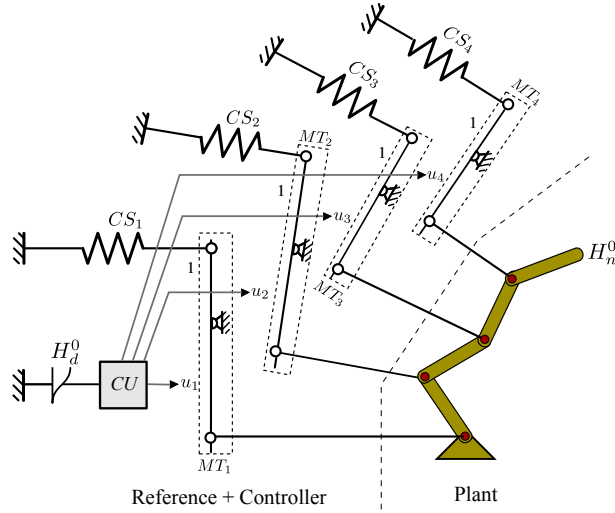


Figure 3.9: Physical depiction of the energy tank based controller for multi-DOF manipulator consists of desired configuration H_d^0 , correct configuration H_n^0 , storage tanks CS_n , modulated transmissions MT_n , modulating factors u_n and computational unit CU .

The port Hamiltonian equation of the tank based system shown in Figure 3.9 can be written as

$$\begin{pmatrix} \dot{s} \\ \tau \end{pmatrix} = \begin{pmatrix} 0 & u \\ -u & 0 \end{pmatrix} \begin{pmatrix} s \\ \dot{q} \end{pmatrix} \quad (3.40)$$

,where $s = [s_1 \dots s_n] \in \mathbb{R}^n$ is a vector representing the state of the spring like storage elements CS , $\dot{q} \in \mathbb{R}^n$ is the joint velocity vector and $\tau = [\tau_1 \dots \tau_n] \in \mathbb{R}^n$ is the joint torque input to the manipulator.

Taking the second half of equation (3.40), any desired torque τ_n can be exerted at joint n on the plant by choosing the desired modulating factor u_{d_n} as

$$u_{d_n} = \frac{-\tau_n}{s_n} \quad (3.41)$$

In order to ensure energetic passivity of the controller, the parameter u should ensure that power flows from a storage tank CS_n to the plant only if there is minimum available energy remaining in the tank. If the energy in the storage tank CS_n is below a threshold minimum value, the controller isolates the storage tank

and the plant by setting the transmission ration $u_n = 0$. Thus, the modulating parameter u_n is finally implemented as

$$u_n = \begin{cases} 0 & \text{if } ((H(CS_n) < \epsilon) \wedge (P_{c_n} > 0)) \\ \frac{-\tau_n}{s_n} & \text{otherwise} \end{cases} \quad (3.42)$$

where τ_n is desired torque at n^{th} joint actuator, $H(CS_n) = \frac{1}{2}s_n^2$ is energy in tank n , ϵ is the minimum energy in the tanks for power to flow towards the plant and $P_{c_n} = \tau_n \dot{q}_n$ is the power flowing from the controller to the plant at the corresponding joint.

3.4.2 Summary of Controller Design Procedure for Multi-DOF Manipulator

Given a desired damping behavior ζ , maximum end-effector velocity $v_{n_{max}}^{0,0}$ and a performance requirement of maximum motion error e_{max} , the control scheme proposed for a multi-DOF manipulator is summarized as follows,

- i Define a preliminary diagonal inertia matrix I_p and calculate the desired cartesian stiffness and damping parameters that satisfy the performance requirement on the inertia using (3.36)
- ii Use joint states q and \dot{q} to compute the Jacobian $J(q)$ and joint space inertia matrix $M(q)$
- iii Compute parameter λ that determines the upper bound diagonal inertia using eq (3.39)
- iv Scale the cartesian impedance parameters calculated in step i according to parameter λ .
- v Determine the wrench W^0 exerted by the scaled cartesian impedance using (3.10) and (3.11)
- vi Define the corresponding joint torque vector by adding compensation terms as given in (3.13)
- vii Compute the modulating parameter u_n of the tank based implementation for the desired joint torques as in (3.42)

3.5 Simulation and Experiment Results

3.5.1 1 DOF Manipulator

In order to evaluate the performance based impedance controller design proposed in section 3.3, two experiments were performed on a 1-DOF setup shown in Figure 3.10. The setup consists of a simple 1 DOF lightweight manipulator with link

inertia of $J = 0.002kgm^2$ actuated through a controlled DC motor. The first positioning experiment investigates whether the impedance controlled plant can achieve desired performance requirements while the follow up experiment evaluates the effect of varying the controller injected stiffness k on system performance.



Figure 3.10: A 1 D.O.F experimental setup used

The experiment used a setpoint position which has a maximum speed of $\dot{x}_{d_{max}} = 2rad/s$ and the desired performance requirement of the link was to accomplish a critically damped behavior with a maximum allowed error of $e_{max} = 0.1rad$. Following the control design procedure summarized at the end of section 3.3, first the damping ratio was chosen as $\zeta = 1$ and then the scaling parameter A is selected based on a desired maximum phase-lead. To make this selection, the maximum controller phase lead ϕ_{max} given in (3.27) was plotted for different values of A and the scaling parameter is set as $A = 15$ to achieve a maximum phase-lead of 65° . See the plot in Figure 3.11.

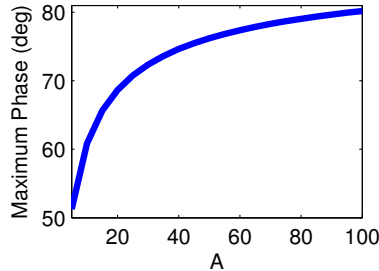


Figure 3.11: Design parameter A vs. maximum phase lead for $\zeta = 1$

Afterwards, the maximum phase lead frequency was computed as $\omega_m = 93.3rad/sec$ and the controller parameters were set as $k = 3.36Nm/rad$ and $b = 0.168Nms/rad$. The experimental results indicate a motion behavior in which the motion error follows the profile of the desired velocity \dot{x}_d and achieves a maximum value of $e_{max} = 0.106rad$ which is very close to the desired performance requirement. See Figure 3.12. The experimental results also indicated a steady state error of $e_{ss} = 0.009rad$ caused by uncompensated disturbances in the system such as friction.

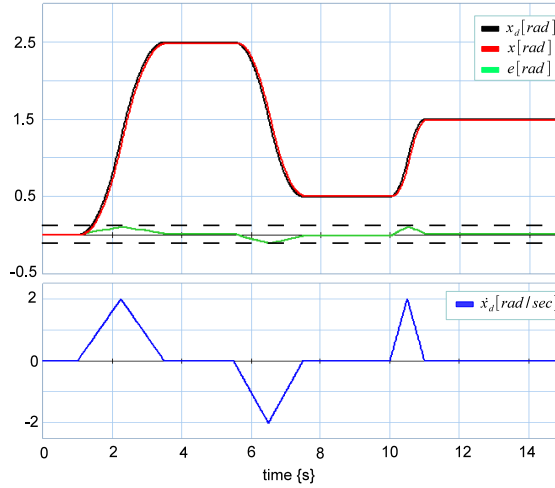


Figure 3.12: Experimental result - Desired position x_d , actual position x , motion error e and the desired velocity profile \dot{x}_d . The dotted line indicate the allowed error tolerance.

On the second experiment, the performance of the system was evaluated for different compliance parameter k . As seen from the experimental results in Figure 3.13, increasing the compliance (lowering the stiffness parameter k) increases both the tracking as well as set point motion error.

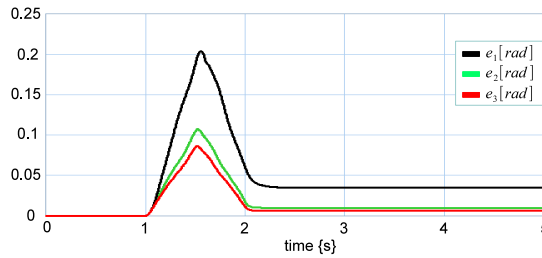


Figure 3.13: Experimental result - Motion errors e_1 , e_2 , e_3 for $k = 1 \text{ Nm/rad}$, $k = 3.6 \text{ Nm/rad}$ and $k = 5 \text{ Nm/rad}$ respectively.

3.5.2 Multi-DOF Manipulator

In the multidimensional case, the impedance controller was designed to achieve a critically damped behavior and a maximum absolute motion error of $e_{max} = 0.01 \text{ m}$ for a maximum end-effector velocity of $v_{n_{max}}^{0,0} = 0.2 \text{ m/s}$.

Following the controller design procedure of multi-DOF manipulators outlined in section 3.4.2, a preliminary diagonal inertia of $I_p = 0.1 \cdot I^{6 \times 6}$ was chosen and

appropriate cartesian impedance parameters that satisfy the given performance requirement on the inertia were computed using (3.36). For a damping ratio of $\zeta = 1$, desired stiffness and damping constants were determined to be $k_t = 160$ and $b_t = 8$ respectively and the performance of the system was evaluated with simulation. Simulation results in Figure 3.14 indicate that the system accomplishes a critically damped behavior with a bounded error that follows the profile of the velocity magnitude as indicated in (3.35) .

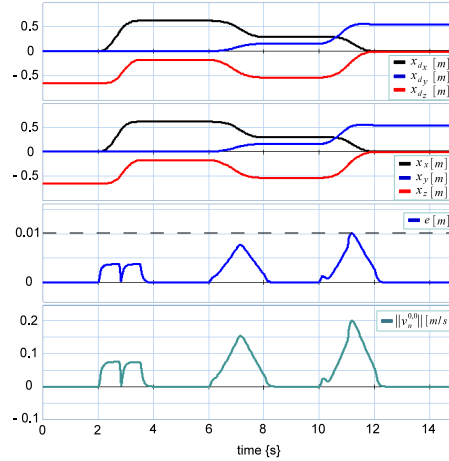


Figure 3.14: Simulation Results: Desired position x_d , actual position x , motion error e and magnitude of velocity $v_n^{0,0}$ on impedance controlled multidimensional inertia.

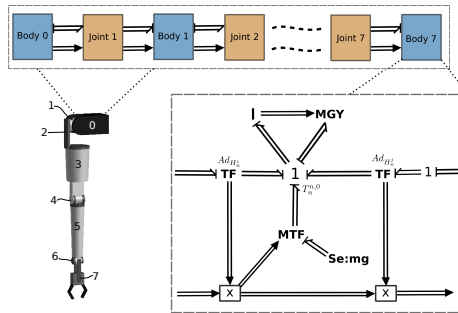


Figure 3.15: The Modeled Manipulator

The multidimensional impedance controller design for multiple DOF manipulator was evaluated on a realistic dynamic model of a 7 DOF manipulator. The model was done using bond graph language that follows a power continuous port based approach to model physical systems [161]. Due to its physical nature, the controller can also be represented in the bond graph language to have a seamlessly

integrated system model. The modeled manipulator, whose moving part weighs $4kg$, mimics a human arm like movements with a 3-DOF shoulder, a 2-DOF elbow and a 2-DOF wrist joints. See Figure 3.15.

The energy tank based impedance controller implementation on a manipulator uses the cartesian impedance parameters computed for the preliminary inertia I_p and modify them to achieve a similar performance behavior on an upper bound diagonal inertia. The controller compares the kinetic energy of the manipulator and that of the preliminary inertia with a similar twist as the end-effector and determines the scaling parameter λ that defines the upper bounded inertia matrix I_m . Then the final desired cartesian impedance that guarantees the performance requirements are determined accordingly using λ .

Simulation results in Figure 3.16 indicate that the controller modify its cartesian impedance to limit the motion error within the tolerance value. In order to compare the effect of the impedance variation, the simulation was repeated without parameter scaling and the results indicate that the performance of the system diminishes without the modifications.

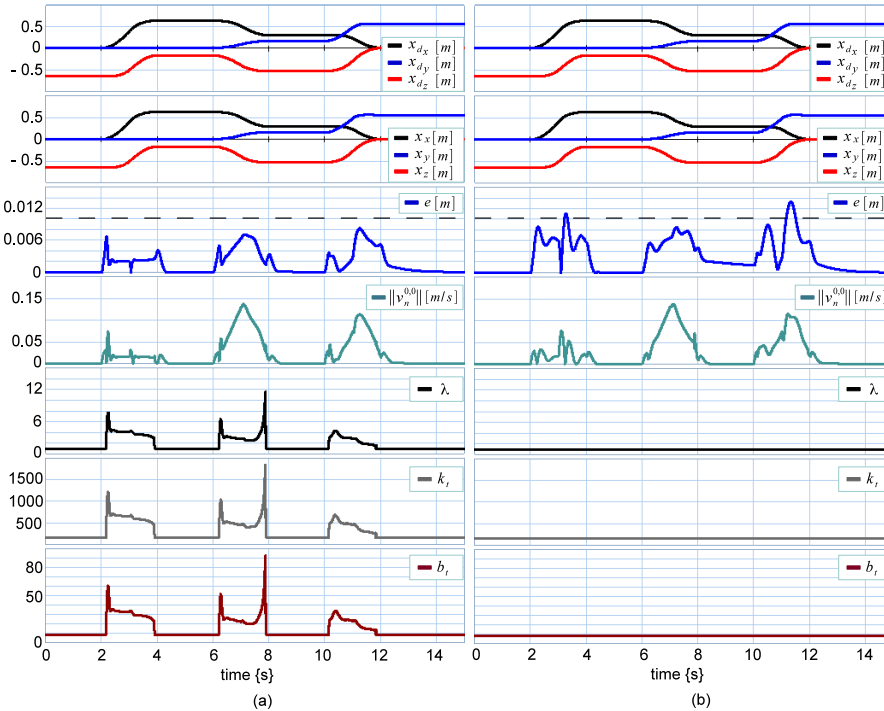


Figure 3.16: Simulation Results: Desired position x_d , actual position x , motion error e and magnitude of end-effector velocity $v_n^{0,0}$, scaling parameter λ , stiffness constant k_t and damping constant b_t of a human-friendly manipulator with a performance guaranteeing variable cartesian impedance controller in (a) and a constant cartesian impedance controller without performance requirement consideration in (b).

The control design was also evaluated for an improved performance requirement of maximum allowed motion error $e_{max} = 0.005m$. Satisfactory results were observed as the controller achieves the desired behavior using initial impedance parameters of $k_t = 640$ and $b_t = 16$. See Figure 3.17.

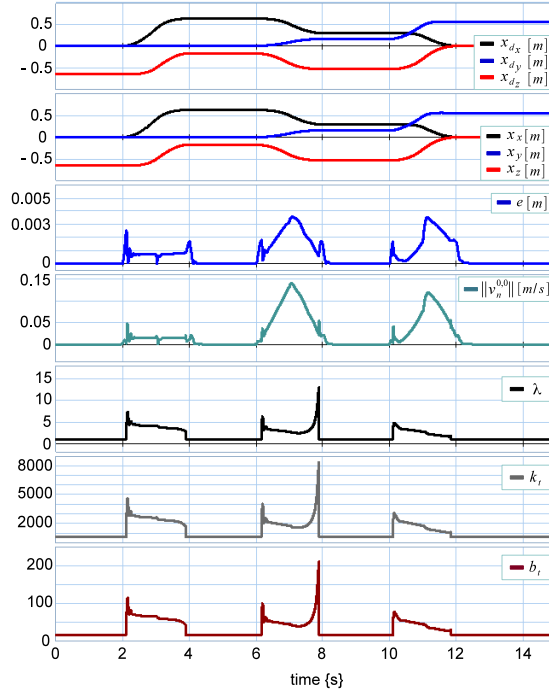


Figure 3.17: Simulation Results: Desired position x_d , actual position x , motion error e and magnitude of end-effector velocity $v_n^{0,0}$, scaling parameter λ , stiffness constant k_t and damping parameter b_t of a human-friendly manipulator with variable cartesian impedance controller.

3.6 Conclusion

This chapter introduced a controller design approach that addresses performance issues of impedance controlled human-friendly manipulators. Safety and performance issues for such manipulators demand conflicting impedance behaviors and this work proposes a method to define the desired impedance characteristic to achieve a performance requirement given in terms of the maximum positional deviation and the required damping behavior. The method uses a frequency domain based performance analysis of linear time invariant systems to define the necessary impedance behavior for a simple 1-DOF manipulator. The full control design procedure for the simple case is recapped at the end of section 3.3. The multi-dimensional extension of the method uses a decoupled motion behavior to handle

performance issues of a rigid body with diagonal inertia moving in cartesian space. Assuming compensated gravitational, Coriolis and centrifugal forces, the controller for an n-DOF manipulator uses the worst-case, upper bound, diagonal operational space inertia to design a passivity based, variable impedance controller that meets the necessary performance requirements. The computation of the upper bound inertia uses a physically interpretable approach and avoids any invertible matrix requirements. While a conservative choice of this matrix might result in unnecessary stiff behavior in the manipulator, it can compensate for model uncertainties and dynamic effect of the Coriolis and centrifugal forces. The overall design procedure summarized in section 3.4.2 indicates that the controller is a straight forward implementation that can be applied successfully.

The control scheme was validated using experiments for the simple case and simulation results for a multi-DOF manipulator. One factor that can negatively influence the system from achieving its performance requirement is the presence of joint frictional forces. Hence, appropriate friction compensation should be added to the controller to minimize the effect of friction. Since the control design is based on the plant parameters, the attainable system performance is susceptible to modeling uncertainties. But the passivity nature of the controlled system avoids any stability concerns due to these model uncertainties. Analysis of possible joint flexibility, saturation issues and other actuator dynamics should also precede the practical investigation of the control technique on human-friendly manipulators.

CHAPTER 4

SAFETY AWARE CONTROLLER DESIGN FOR HUMAN-FRIENDLY MANIPULATORS

“Simplicity is the ultimate sophistication.” Leonardo da Vinci

This chapter presents a general interaction controller design approach that extends the standard impedance controller with a combined energy and power based safety norms to ensure safety of robotic manipulators. Safety of such robots is a crucial concern that should be addressed because domestic robots operate in an environment shared with a human user. The most serious hazard due to the cohabitation of the same space is a collision risk that can cause wide range of injuries to the human. Different safety metrics are proposed to analyze injury levels of uncontrolled collision and provide essential methods to quantitatively determine whether a robot achieves an adequate safety level or not. For human-friendly manipulators, efficient operation is achieved by using impedance controller in combination with passivity theory to introduce compliant behavior and ensure asymptotic stability of the system. The controller proposed in this work extends the standard impedance control scheme with energy and power based safety metrics to assert that safety requirements defined in these norms are achieved by domestic robots. The proposed controller adopts a passive system design approach and its effectiveness is illustrated with simulation and experimental results.

This chapter is an extended version of the publication: T.S. Tadele, T.J.A de Vries and S. Stramigioli, “Combining Energy and Power based Safety Metrics in Controller Design for Domestic Robots,” *2014 IEEE International Conference on Robotics and Automation (ICRA)*, Jun 2014

4.1 Introduction

Possible use of domestic robots as dependable human assistants relies on a comprehensive safety investigation against a number of potential risks and injuries. As stated in Chapter 2, standard safety analysis a robotic system is done by using a systematic, risk based and multistage procedure. Considering the case of domestic robot manipulators, the most likely feasible and crucial risk is an uncontrolled impact with a human user. As a result, most safety centered works in human-friendly manipulators focus on a collision risk along with its respective injury levels, mitigation solutions and safety norms. The collision between the robot and the human can be either a clamped contact, where a body part is squeezed between the robot and a fixed constraint, or unclamped contact, where the body freely reacts to the collision [70]. See Figure 4.1. Depending on cover material, shape of the manipulator at the contact point and impact strength, the injury on a human can range from light bruises to serious body harm.

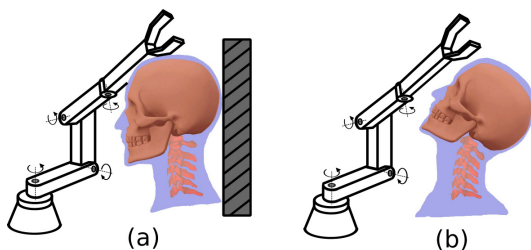


Figure 4.1: (a) Clamped collision (b) Unclamped collision

A widely used strategy to minimize potential injuries from a collision risk in human-friendly manipulators is to adopt a lightweight and compliant design of the manipulators. The controller design of these manipulators deals with regulating the system compliance, ensuring stability and managing task accomplishment. A passivity based impedance control has been identified as a convenient control strategy that satisfies all these requirements [78, 176, 3, 208, 143]. Such a control scheme uses a physically interpretable design in which the dynamics of the manipulator is shaped to realize a compliant behavior with a guaranteed asymptotic stability even during interaction with an unknown passive environment.

Even with the lightweight and compliant designs, quantitative analysis of collision induced injury levels on a human should be conducted by using different safety metrics which are presented in section 2.2. Design modifications in the controller or any other part of the robotic system that aim to minimize collision risks can use these metrics to verify whether safety improvements are achieved or not in the manipulator. While the metrics are necessary to define potential injury levels of a collision risk, their exploitation for the design of safety aware controllers has been minimal. Control schemes that incorporate safety norms in their design identify an appropriate metric and propose solutions that guarantee safety either by using

a pure control action or changing the desired motion profile input to the controller [75, 15, 113].

The suitability of using impedance controllers for human-friendly manipulators can be further boosted if the safety of the manipulator against well known risks is guaranteed by incorporating safety metrics in the controller design. A novel control design technique that allows the standard impedance control design to detect and avoid potentially unsafe collision risks was introduced in our previous work [179]. The safety aware controller design combines energy and power based metrics that address different injury types and utilizing them together ensures safety of the manipulator against injuries defined in both metrics. Given current states of the manipulator, the proposed model based controller modifies its parameters to guarantee that safety requirements defined in the metrics are met. To ensure overall passivity and energy consistency of the system, the variable impedance controller is implemented using an energy tank based system. The controller design methodology is easily elaborated on a simple 1-DOF manipulator and its generalized multidimensional extension that handles multi-DOF open chain serial manipulators is introduced in this chapter.

This chapter is organized as follows. In section 4.2 design considerations for a safety aware controller are presented. Then sections 4.3 and 4.4 discuss the proposed combined safety norm and controller design for simple and multi-link manipulators respectively. Section V presents simulation and experimental results before section VI summarizes the main ideas and presents the conclusions.

4.2 Design Considerations

A robotic system is labeled safety-aware if it incorporates information regarding the potential injury it can cause [67]. The injury level is represented by using different safety metrics which are defined on the basis of well known risks. A controller that aims to ensure safety of human-friendly manipulators against collision risks should thus identify an appropriate safety metric to identify and manage the injuries resulting from the impact. Information from different safety metrics which address distinctive injuries can also be combined in the controller design to offer an enhanced protection against multiple unsafe scenarios. Among the different safety metrics of collision injuries presented in 2.2, energy and power based metrics were identified as metrics of choice in the controller design. These metrics are more suitable for use on human-friendly manipulators over the widely known HIC which has a clear drawback in low speed collision injuries [180]. The energy and power based safety metrics are intuitive as well as physically meaningful and can easily fit into the passivity based impedance controller design. Moreover, they are capable of handling both clamped as well as unclamped impacts against a human user.

In a realistic use-case a domestic robot can operate far from a human, near an adult or even near a child and the corresponding safety instructions for the robot can be defined in human understandable terminology as ‘be careful’, ‘be

very careful' and 'be extremely very careful'. Similarly a given safety metrics could establish injury levels that depend on the operating conditions of the robot and the environment. If an energy based metric is used for example, the allowed energy tolerance level can be $50J$, $30J$ and $5J$ for the three cases. As a result a safety aware controller design should support a flexible design where time varying injury levels could also be used.

In a robotic system, the direct interconnection between the motion planner and the controller can be exploited in such a way that detected unsafe conditions are avoided indirectly by modifying the motion planner outputs to the controller. While this methodology uses the controller to achieve a safety modified motion trajectory, it is susceptible to failures in the motion planning component. A truly safety aware controller should be a self-reliant system that can guarantee safe operation even when the motion planner is faulty.

4.3 Safety aware impedance controller for Simple Manipulators

The design of the impedance controller as physically interpretable dynamic system allows the analysis of its energy content and power exchange with the manipulator [142]. Given the impedance controlled system shown in Figure 2.4, total energy of the overall system is the sum of the kinetic energy of the plant and the potential energy of the controller spring. It is given as

$$E_{tot} = \frac{1}{2}kx_e^2 + \frac{1}{2}m\dot{x}^2 \quad (4.1)$$

where $x_e = x_d - x$ is the motion error which is equal to the state of the controller spring and \dot{x} is velocity of the plant.

Given a safety metric defined energy threshold that a human body can tolerate without sustaining injury, the controller can be designed in such a way that the maximum energy content of the overall system is below the threshold value. From (4.1) it can be seen that a system designer can use the desired trajectory x_d , the controller stiffness k or a combination of both parameters to restrict the total energy E_{tot} of the controlled manipulator below a maximum allowed value E_{max} . A controller which guarantees safety of a manipulator irrespective of the desired trajectory input can be implemented by modifying its stiffness parameter as

$$k = \begin{cases} k_o & \text{if } E_{tot} \leq E_{max} \\ \frac{2E_{max} - m\dot{x}^2}{(x_d - x)^2} & \text{if } E_{tot} > E_{max} \end{cases} \quad (4.2)$$

where k_o is the maximum controller stiffness mainly chosen based on performance requirements and m is the mass of the plant.

Once the safe energy restrictions are ensured by the stiffness choice, the maximum power that the manipulator can transfer to a human during collision can be limited via a control action. Since a robotic manipulator is guided by controlled actuators while performing its tasks, the amount of power it can transfer to a human during uncontrolled impact can be limited by regulating the power flow from the actuators to the manipulator. For an impedance controller, the power flowing from the controller to the plant P_c is given as,

$$P_c = (k(x_d - x) - b\dot{x})\dot{x} \quad (4.3)$$

where k and b are the stiffness and damping terms of the controller.

Then for a fixed controller stiffness k , the power flow between the plant and controller can be limited to maximum value $P_{c_{max}}$ by adjusting the damping parameter b as follows,

$$b = \begin{cases} b_o & \text{if } P_c \leq P_{c_{max}} \\ \frac{k(x_d - x)\dot{x} - P_{c_{max}}}{\dot{x}^2} & \text{if } P_c > P_{c_{max}} \end{cases} \quad (4.4)$$

As a result, the controller implementation demands continuous monitoring of the total energy in the system along with the power transfer to the manipulator. When the total energy exceeds above a threshold value, the controller becomes more compliant to trim the total energy and when a potentially unsafe power output is detected the controller adds more damping to lower the controller torque output. Once appropriate controller parameters are determined for a given manipulator state from equations (4.2) and (4.4), the resulting impedance controller can be written mathematically as,

$$F_c = k \cdot (x_d - x) - b \cdot \dot{x} \quad (4.5)$$

But direct realization of this variable impedance controller affects the passivity of the system and breaches the energetic coupling which is the basis of the standard impedance control design. These problems were also identified for a similar variable impedance controller requirement in section 3.4.1. and an energy tank based controller implementation was used as a viable solution. In the simplified 1-DOF case, the controller design consists of an energy tank CS which behaves like an energy storage spring with a stiffness constant value of 1, a transmission element MT with variable transmission ratio and a computational unit CU that calculate the transmission ratio u . See Figure 4.2.

Once the state of the plant is determined, the computational unit calculates the desired output force of the controller using (4.5) and then selects an appropriate transmission ratio that scales the output force of the storage tank to obtain the desired amount of force at the plant. The transmission ratio is also used to update the state of the storage tank depending on the measured plant states. Since the overall dynamic system is passive by design, its stability is always guaranteed as long as it is interacting with passive systems.

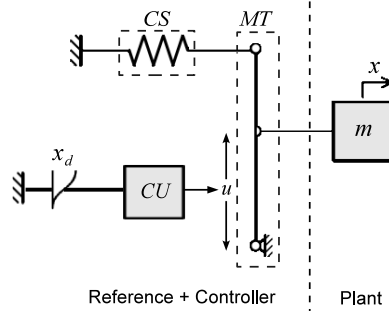


Figure 4.2: Energy tank based controller design.

The port Hamiltonian equation of the tank based system shown in Fig 4.2 can be written as

$$\begin{pmatrix} \dot{s} \\ \dot{p} \end{pmatrix} = \begin{pmatrix} 0 & u \\ -u & 0 \end{pmatrix} \begin{pmatrix} s \\ p/m \end{pmatrix} \quad (4.6)$$

where s is state of the spring like storage CS which is equal to its force output, p is the momentum of the plant and $p/m = \dot{x}$ is velocity of the plant.

After a desired impedance controller output force F_c is computed using (4.5), the second half of equation (4.6) can be used to select a desired transmission ratio u_d as

$$u_d = \frac{-F_c}{s} \quad (4.7)$$

Similar to the multidimensional implementation, the controller design requires a physically consistent energy coupling which dictates that power must flow from the tank to the plant only if there is adequate amount of energy stored in the tank. Thus if the controller wants to transfer power to the plant while there is a depleted amount of energy in the tank, then the transmission ratio u should ensure that the controller and the plant are isolated. As a result, this passivity ensuring relation can be defined by choosing the variable transmission ratio parameter u as

$$u = \begin{cases} 0 & \text{if } ((H(CS) < \epsilon) \wedge (P_c > 0)) \\ \frac{-F_c}{s} & \text{otherwise} \end{cases} \quad (4.8)$$

where F_c is desired output controller output force, $H(CS) = \frac{1}{2}s^2$ is the potential energy in the tank, ϵ is the minimum energy required in the tank for power to flow towards the plant and $P_c = F_c \dot{x}$ is the power flowing from the controller to the plant.

4.4 Extension to Multi-DOF Manipulators

The multidimensional cartesian space impedance controller discussed in section 3.2.2 can also be integrated with appropriate safety metrics to guarantee safety

of a human user sharing a workspace with a multiple DOF manipulator. In this analysis we will consider manipulators in which the damping is injected in the joint space by using dampers b_n in each DOF. See Figure 3.1. The resulting cartesian impedance control law then becomes,

$$\tau = J^T(q) \cdot W_k^0 - \bar{B}\dot{q} + \hat{C}(q, \dot{q})\dot{q} + \hat{G}(q) \quad (4.9)$$

where W_k^0 is the cartesian wrench due to the spatial spring represented in coordinates of an inertial reference frame, $\bar{B} \in \mathbb{R}^{n \times n} = \text{diag}([b_1 \dots b_n])$ represents a matrix of joint damping parameters, $\dot{q} \in \mathbb{R}^n$ is vector of joint velocities and $\tau \in \mathbb{R}^n$ is the vector of joint torques.

The adoption of the energy based safety metric on the cartesian impedance controller design demands evaluating the total energy content of the controller as well as the manipulator. For a control law defined in (4.9), the total energy in the system is the sum of the kinetic energy of the manipulator and the potential energy due to the spatial springs. Since the centrifugal and Coriolis forces do no work, the total kinetic energy of the manipulator T is defined as

$$T(q, \dot{q}) = \frac{1}{2} \dot{q}^T M(q) \dot{q} \quad (4.10)$$

where $M(q)$ is the inertia matrix and \dot{q} is the vector of joint velocities. The potential energy due to the spatial compliance is by itself a sum of the translational, rotational and coupling energies

$$V(R_t^d, p_t^d) = V_t(R_t^d, p_t^d) + V_o(R_t^d) + V_c(R_t^d, p_t^d) \quad (4.11)$$

where R_t^d and p_t^d are the rotational and position of the relative configuration. These energies are given as [54, 176]

$$V_t(R_t^d, p_t^d) = -\frac{1}{4} \text{tr}(\tilde{p}_t^d G_t \tilde{p}_t^d) - \frac{1}{4} \text{tr}(\tilde{p}_t^d R_t^d G_t R_t^d \tilde{p}_t^d) \quad (4.12)$$

$$V_o(R_t^d) = -\text{tr}(G_o R_t^d) \quad (4.13)$$

$$V_c(R_t^d, p_t^d) = \text{tr}(G_c R_t^d \tilde{p}_t^d) \quad (4.14)$$

where $\text{tr}()$ is the tensor trace operator.

The energy based safety metric demands a limit on the total energy of the system and this can be achieved by regulating the amount of potential energy in the spatial springs of the control system. Since all the three energies are proportional to the corresponding co-stiffness matrices [54], the co-stiffness matrices can be scaled proportionally to modify the potential energy and hence the total energy in the system. If a set of co-stiffness matrices are chosen initially as G_{x_i} , then the energy content of the system will become

$$E_{tot_i} = T(q, \dot{q}) + V_i(R_t^d, p_t^d) \quad (4.15)$$

where $V_i(R_t^d, p_t^d)$ is the potential energy due to the initial co-stiffness matrices.

The final set of co-stiffness matrices G_x can be defined as a function of a scaling parameter λ as

$$G_x = \lambda \cdot G_{x_i} \quad (4.16)$$

and total energy after the co-stiffness modification can be limited to a maximum allowed value E_{limit} by selecting the scaling parameter as

$$\lambda = \begin{cases} 1 & \text{if } E_{tot_i} \leq E_{max} \\ \frac{E_{limit} - T(q, \dot{q})}{V_i(R_t^d, p_t^d)} & \text{otherwise} \end{cases} \quad (4.17)$$

In the end, the total energy of the controlled system

$$E_{tot} = T(q, \dot{q}) + \lambda \cdot V_i(R_t^d, p_t^d) \quad (4.18)$$

is always less than or equal to the energy due to the initial choice of co-stiffness matrices E_{tot_i} and the scaling will make sure it is also less than the maximum allowed tolerance value E_{limit} .

Once the co-stiffness parameters that satisfy appropriate energy content in the system are determined, injury types covered under the power based safety metrics can be avoided by limiting the power that is transferred from the controller to the plant. If the joint damping matrix is chosen initially as \bar{B}_i , using (4.9) the power transferred from the controller during the movement of the manipulator is given as

$$P_{c_i} = \underbrace{(J^T(q) \cdot W_k^0 - \bar{B}_i \dot{q})^T \cdot \dot{q}}_{P_{c_m}} + \underbrace{\hat{G}(q) \cdot \dot{q}}_{P_{c_g}} \quad (4.19)$$

where W_k^0 is the wrench due to the spatial spring after the energy limit modifications.

Note that part of the instantaneous power flowing to the plant is due to the impedance controller and results in movement of the manipulator while the remaining power is consumed to compensate gravity and keeping the manipulator at its current configuration. Due to the consumption of the gravity compensation power by the manipulator itself, the power that can be transferred to a human in case of uncontrolled contact is the motion driving power indicated as P_{c_m} in (4.19).

If a damping scaling parameter β is chosen such that

$$\bar{B} = \beta \cdot \bar{B}_i, \quad (4.20)$$

then the scaling parameter can be used to limit the maximum motion driving power P_{c_m} below its tolerance value P_{max} when

$$\beta = \begin{cases} 1 & \text{if } P_{c_m} \leq P_{max} \\ \frac{(J^T(q) \cdot W_k^0)^T \cdot \dot{q} - P_{max}}{\dot{q}^T \bar{B}_i \dot{q}} & \text{otherwise} \end{cases} \quad (4.21)$$

To summarize, the controller monitors the energy of the controlled system and the power flow from the controller to the plant in order to scale the cartesian stiffness and joint damping parameters. Similar to the simplified case discussed in the previous section, problems due to direct implementation of this variable impedance controller was solved by using the energy tank based design presented in section 3.4.1.

The controller design can be summarized in a multilayered structure where the torque outputs of the primary motion layer are investigated in the successive safety and passivity layers. See Figure 4.3. This passivity based, safety aware impedance controller design results in a compliant, human-friendly manipulator that remains stable during interaction with a passive environment.

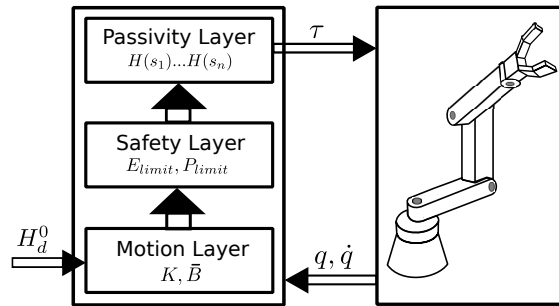


Figure 4.3: Layered structure of the proposed controller.

4.5 Simulation and Experiment Results

4.5.1 Simple Manipulator

The safety integrated impedance controller design proposed for simple manipulators was investigated using experiments performed on a 1-DOF setup shown in Figure 4.4. The setup consists of a single link manipulator with inertia of $J = 0.0069 \text{ Kg m}^2$ and a controlled DC motor for actuation.

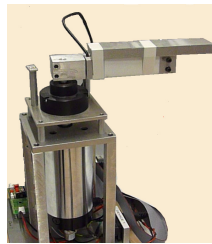


Figure 4.4: A 1 D.O.F experimental setup used

The first experiment was aimed at evaluating the controller as well as the complete system during a standard trajectory tracking that was free from interaction with the environment. As a proof of concept a the safety criteria limits were set as a maximum allowed energy limit of $E_{max} = 0.05J$ and a power limit of $P_{Cmax} = 0.1W$ used as safety criteria limits while the initial stiffness and damping ratio of the controller were chosen as $k_{c_o} = 3.5Nm/rad$ and $b_o = 0.17Nms/rad$. The experimental results shown in Figure 4.5 and 4.6, indicate that the controller was able to position the plant at the desired position while keeping the safety limits by modifying its compliance and damper parameters.

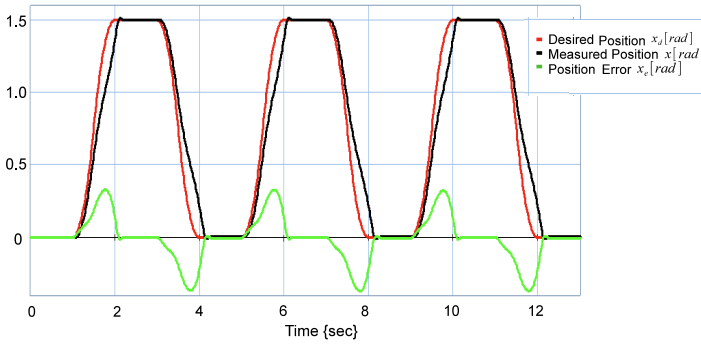


Figure 4.5: Experimental results (Free motion) - Trajectory tracking with no interaction

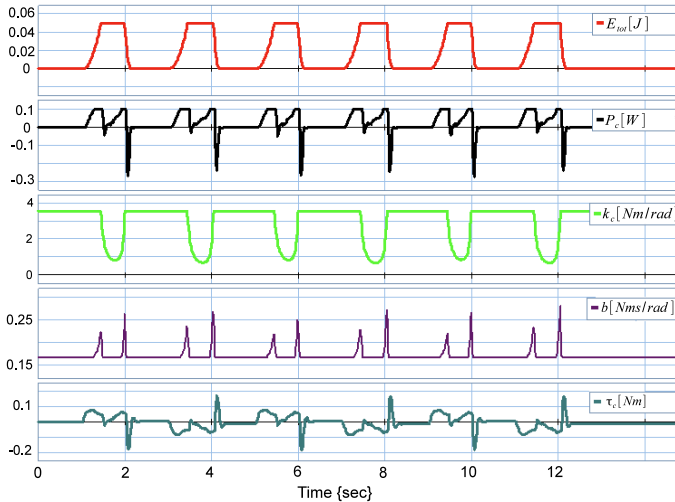


Figure 4.6: Experimental results (Free motion) - Total energy of impedance controlled system E_{tot} , power flow from the controller to the plant P_c , stiffness of the system k_c , damping ratio b and controller torque output τ_c

In order to analyze the effect of the safety integrated variable impedance controller on system performance, the experiment was repeated using a standard impedance controller with fixed parameters of $k_c = 3.5Nm/rad$ and $b = 0.17Nms/rad$. In the results shown in Figure 4.7, it can be seen that the safety requirement is achieved through a compliant manipulator at the expense of an increase in motion error.

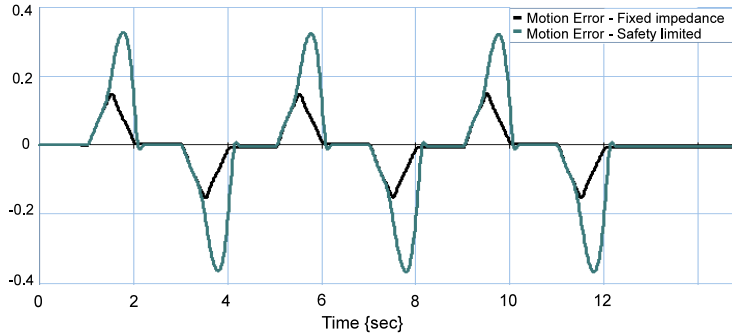


Figure 4.7: Experimental results - Motion Error using an impedance controller with and without safety requirements

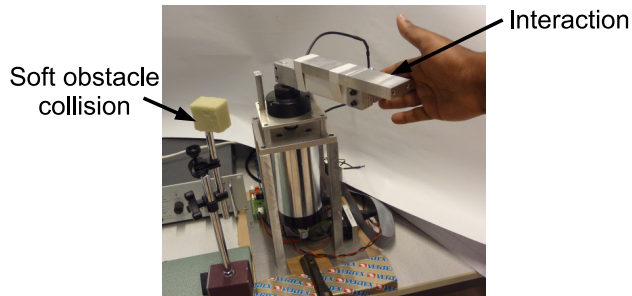


Figure 4.8: Collision and interaction experiment

In the next experiment, the controller behavior and overall stability of the system was evaluated during collision with a soft obstacle and interaction with a human user. Using safety criteria tolerance limits of maximum allowed energy $E_{max} = 0.075J$ and maximum power $P_{c_{max}} = 0.15W$, the experiment was designed to mimic realistic situations where a human user is squeezed or suddenly impacted by a manipulator. The system remained stable throughout the experiment and safety metric limitations were maintained by the controller during the soft collision as well as the interaction. See Figure 4.9.

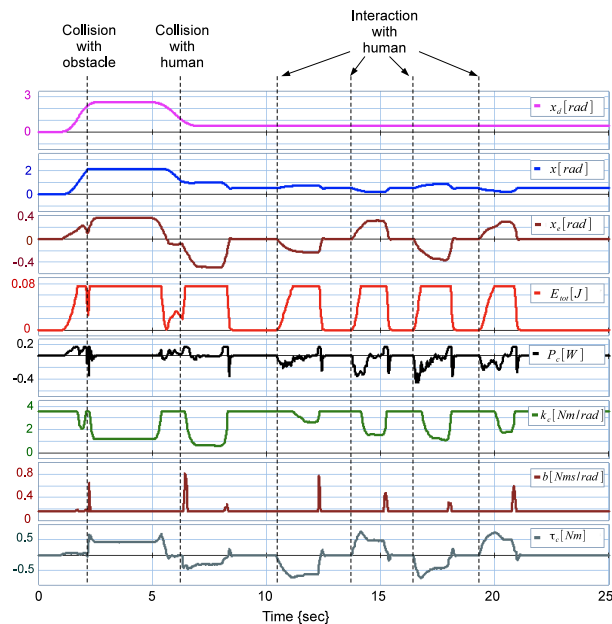


Figure 4.9: Experimental results - Desired position x_d , measured position x , position error x_e , total energy of impedance controlled system E_{tot} , power flow from the controller to the plant P_c , stiffness of the system k_c , damping ratio b and controller output torque τ_c

4.5.2 Multiple DOF Manipulator

The safety aware impedance controller design for multiple DOF manipulator was validated on a dynamic model of a lightweight 7-DOF manipulator that imitates a human arm with a 3-DOF shoulder, 2-DOF elbow and 2-DOF wrist joints. The manipulator was modeled in bond graph language that uses a power port based approach to represent dynamic behavior of physical systems [161].

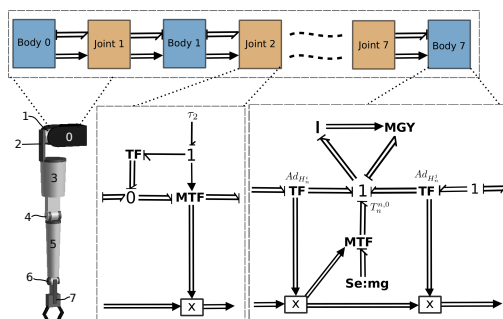


Figure 4.10: The Modeled Manipulator

The model was used to evaluate the controller design as the manipulator moves towards a desired end-effector configuration in the operational space and collides with a rigid obstacle. A time varying safety limits was adopted as

$$\begin{cases} E_{max} = 1J \ \& \ P_{c_{max}} = 0.5W & 0 < t < 6 \\ E_{max} = 0.25J \ \& \ P_{c_{max}} = 1W & 6 \leq t < 15 \end{cases} \quad (4.22)$$

Simulation results in Fig 4.11 show different system parameters of a manipulator with safety aware impedance controller. The system continuously monitors and limits the system energy and power flow within the acceptable tolerance range by scaling the cartesian stiffness and joint damping parameters. The simulation was repeated under a standard impedance controller for comparison and the results presented in Fig 4.12 show that safety imposed parameter changes result in a higher motion error during the free motion and a lower clamping force during contact with an obstacle.

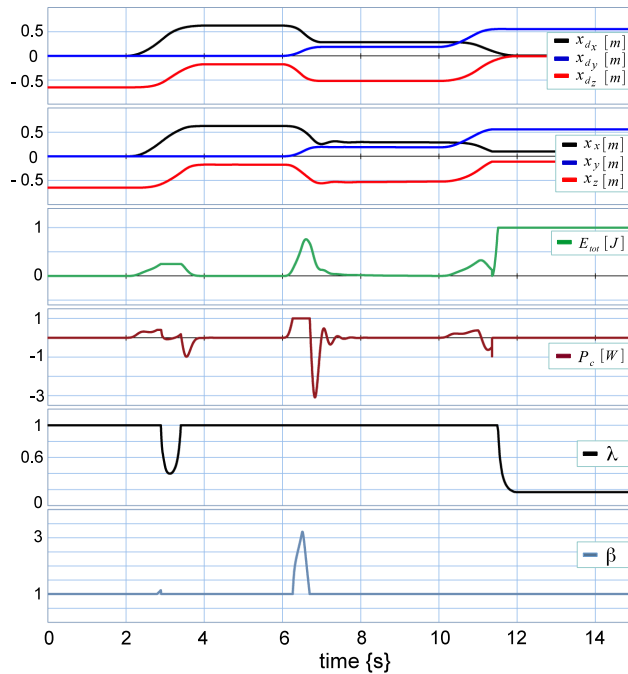


Figure 4.11: Simulation Results: Desired position x_d , actual position x , total energy in the system E_{tot} , controller output power P_c , stiffness scaling parameter λ and damper scaling parameter β of a safety aware cartesian impedance controller for a human-friendly manipulator.

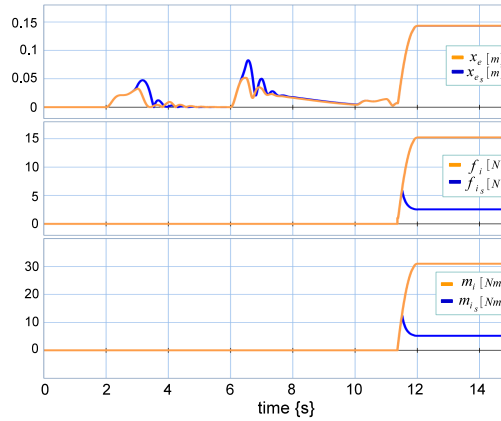


Figure 4.12: Simulation Results: Comparison of the motion error x_e , force exerted on a rigid obstacle f_i and torque exerted on a rigid obstacle m_i between a standard impedance controller and its safety aware adaptation. The subscript s indicates results of the system with safety integrated controller.

4.6 Conclusion

This chapter presented a novel controller design for human-friendly manipulators that utilizes safety metrics to enhance the standard impedance controller scheme. The design considerations which include use of appropriate safety metric, flexibility to support realistic safety situations and self-reliant system were satisfied in the controller methodology. By monitoring the energy content of the system and the power flow between the plant and the controller, safety requirements defined in terms of energy and power limits are maintained by varying the controller parameters in a passive implementation. The controller design also allows instantaneous modification of the safety limits so that appropriate safety requirements are set depending on the environmental conditions. Simulation and experimental results validated the control scheme for both simple as well as multi-DOF manipulators and they also highlighted the trade-off between safety and performance in which an increase in compliance resulted higher trajectory error.

Even though the apparent frictional forces in the manipulators were not included in the analysis of the controller design, its dissipation behavior ensures that the power reaching the manipulator is even lower than the safety limited tolerance value. Possible future work on this controller design include practical investigation of the multi-DOF manipulator and identification of appropriate energy and power safety limits for a range of possible risks.

CHAPTER 5

TOWARDS A MODULAR DOMESTIC ROBOT: BOBBIE-UT

“Once the product’s task is known, design the interface first; then implement to the interface design.” Jef Raskin

Motivated by the positive contribution of modular design approaches in the automotive and personal computer industry as well as its support for product evolution, it was adopted in the design of a domestic robot which will be used for research. This chapter presents the design of Bobbie-UT, a modular domestic robot built as an interconnection of a manipulator arm, robotic head, mobile platform and torso. The core methodology behind the design of Bobbie-UT is the difference in functionality among separate modular components which are connected with each other through mechanical, data and electric power interfaces. This work points out the necessary functional and safety requirements of each modular component and addresses the design of the in-house made components, the developments carried out on externally acquired components and results of some experiments conducted. Furthermore, a distributed data processing architecture and a component based software development methodology that fit into the modular design of Bobbie-UT are also described.

5.1 Introduction

Recent advances in robotic technology have spurred its adoption beyond the high-tech manufacturing industries and into new application domains such as medical, rescue, logistics, personal care and entertainment. The broad personal care category comprises of service robots such as domestic servant robots, people carriers and standalone or wearable physical assistants that improve the quality of life for an individual [74]. Successful growth in the number of personal care robots which are in use relies upon their dependability, overall cost and acceptance by the end user.

One proposed application of domestic service robots is providing non-critical assistance such as fetching objects, assisting movements and handling doors for elderly and handicapped individuals. Different social and economic factors such as surge in the number of aging population, choice of home care over nursing homes and increased health care cost of home care are driving the need for domestic robots that can serve in home environments[148]. Cleaning and delivery service around office environments also broaden the possible applications of such domestic robots and pave the way for a new commercialization area in robotics [8]. These robots are complex systems that are expected to offer multiple functionality, acceptable performance and guaranteed safety while operating in an unstructured human-present environment.

In order to conduct researches that can contribute to the advancement of domestic service robots, we built a robotic platform that can be deployed around home and office environments. The considerable effort required to build a domestic robot platform and its overall system complexity were managed by using a modular design approach. With this technique, instead of constructing the robot as one complete unit, it is made as an interconnection of interchangeable robotic components. Such a modular design approach requires a well-defined interfaces between the components and it is predominantly used in automotive, computer and construction domains. The methodology reduces complexity, minimizes design time, drives innovation at component level and the possible component variation promotes application flexibility. Furthermore, the partitioning of systems into modular components simplifies fault detection and troubleshooting. Possible downsides of modularity include degradation of performance, possibility of reliability problems and unwanted operational disturbances due to the interfaces [5].

This chapter is organized as follows. In section 5.2 some background information regarding modular design approaches in domestic robots is briefly presented. Section 5.3 covers the development of each modular component making up Bobbie-UT and then discusses its information processing and software architectures. Finally, section 5.4 summarizes the main ideas and presents the conclusions.

5.2 Modularity in domestic service robots

The ever increasing interest in deploying robots as our daily assistants has motivated a number of researches and introduced different domestic robot platforms [73, 159, 182, 9, 202, 90, 18]. See Figure 5.1 The design rationale behind these robots mainly focuses on realizing the necessary functionalities such as perception, mobility, manipulation capability and task execution. Moreover, other essential requirements such as safety, reliability, appearance, modularity and cost reduction have also been addressed together with the design of these domestic robots.

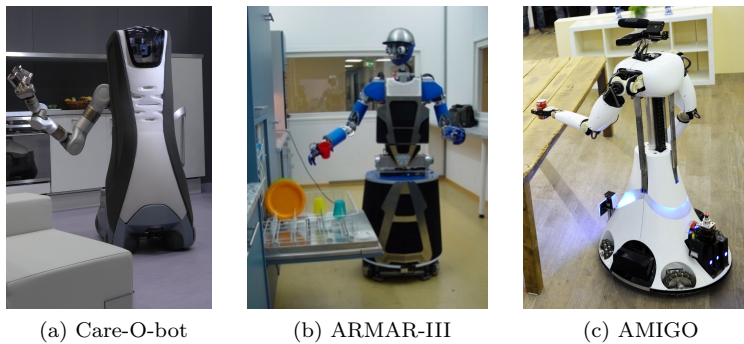


Figure 5.1: Different domestic service robots

To make these robots accessible to a wide research community, modular design has been touted as the only possible solution to address their complexity [196]. Modularity is a systematic design methodology where functions are implemented by modules that can be combined in subsequent designs [5]. So far, the use of modular design in the robotics domain is mainly restricted to small robots that use identical components which are combined in a certain configuration to yield a homogeneous modular system [204]. By adopting the modularity concept in the design of domestic robots, a simplified development that supports innovation and product evolution can be achieved, thereby accelerating their use beyond research laboratories. A favorable technique to apply the design concept in domestic robots is through functional modularity where heterogeneous components with different operational functionality are integrated to form a complete robotic system [182]. Typical modular components include a robotic head with vision capabilities, a mobile platform that can navigate an environment or a hand-arm system that can be used for manipulation.

In order to build the complete robotic system using a rapid and seamless integration of these components, they should all possess standardized electrical, mechanical as well as data communication interfaces. Several hybrid interface concepts that support both mechanical and electrical connection of the modular robotic components have been proposed by manufacturers [10, 166] as well as researchers [109].

See Figure 5.2. In addition to these hybrid interfaces, executing the functionality of the modular components requires a clean software interface that allows product variation, reconfiguration and direct data communication [151].

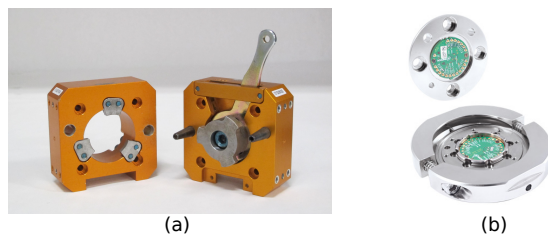


Figure 5.2: Module interfaces: (a) ATI Tool changer interface (b) Schunk Flat Change System

5.3 Bobbie-UT

Bobbie-UT is an average teen-sized humanoid service robot which is built as an integration of a modular humanoid head, 7 DOF manipulator arm, torso and mobile platform. See Figure 5.3. As a platform that facilitates research activities in the application of domestic robots, there are a number of functional and design requirements that are vital during the development of the robot. The functional requirements which demand the inclusion of certain capabilities such as vision, navigation and manipulation are divided among the different modular components. In addition, requirements such as safety and robustness are addressed during the design of all the independent components constituting the robot.

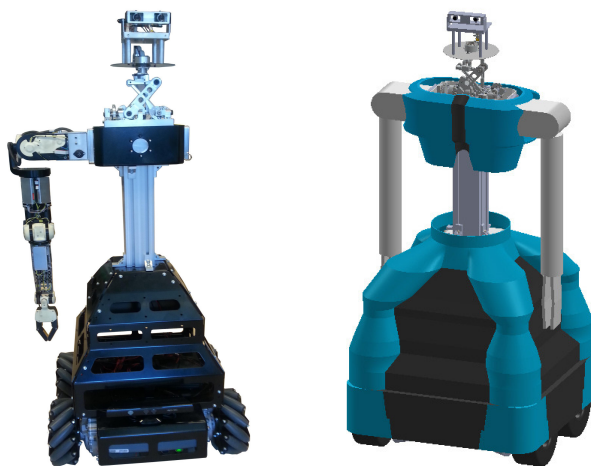


Figure 5.3: Bobbie-UT and rendering of its final look with covers

Building Bobbie-UT started with initial design criteria of reducing cost and lowering development time by using available off-the-shelf hardware and software components. Thus, various open-source software components as well as a ready-made 7-DOF robotic arm and an omni-wheel mobile platform hardware modules were used to achieve an integrated robotic system. To interconnect the components and allow a seamless exchange of components, a set of standards were defined with feasible mechanical interfaces, electrical power connections, data communication capabilities and necessary software architecture. Support for multiple component types, fail-safe redundancy and future modifications were made possible in the design by providing possible use of multiple communication buses and a range of electric power outputs.

Another essential design requirement considered in the design of the robot was safety for the human user, the environment and the robot itself in the unstructured operational environment. Following the standard risk based safety analysis of robotic systems, there are a number of possible risks that can be encountered during the normal operation of the robot [74]. For modular systems, the safety analysis of identified risks should be done both at the system and module levels. Some of the prominent risks considered in the design of Bobbie-UT are impact on a human by the manipulator, collision with an obstacle and falling of the robot after it tips over. After identification of the risks, the development of the various modular components in Bobbie-UT included appropriate design solutions that can mitigate these risks and improve safety of the robot.

5.3.1 Modular components

The functionality based modular robot design followed in Bobbie-UT resulted in four main components that make up the robot. The adoption of the functional modularity concept defines clear module boundaries based on the difference in functionality among different modular components. The different design issues that are important to achieve the desired operation and deal with the vital safety issues of each component is discussed below.

5.3.1.1 Robotic arm

The main manipulation capability of the robot was provided through a 7-DOF robotic arm with a two fingered, compliant and under-actuated gripper. With a total moving mass of 4 kg, full arm length of 80cm and payload capacity of 1.5 kg, the manipulator possesses a human arm like kinematics with shoulder, elbow and wrist like joints. The harmonic drive system and high gear ratio transmissions used in the manipulator result in a slight flexibility in the joints and higher reflected motor inertia at the link side. Each joint of the robotic arm is equipped with an absolute joint position sensor, encoder reading for the actuator position and a torque sensor.

The developments on the robotic arm centered on satisfying a functional require-

ment of possessing an acceptable manipulation capability and safety requirement of achieving a compliance behavior with stable operation. The first work on the robot arm involved the implementation of a cartesian space impedance controller to successfully accomplish manipulation tasks. To assist in the controller design and perform a simulated validation before actual implementation, the manipulator was first modeled in bond graph language that uses a power port based approach to represent dynamic behavior of physical systems [161]. Together with the actuation dynamics, the model represents the manipulator in terms of a power continuous interconnection of rigid bodies and joints. See Figure 5.4.

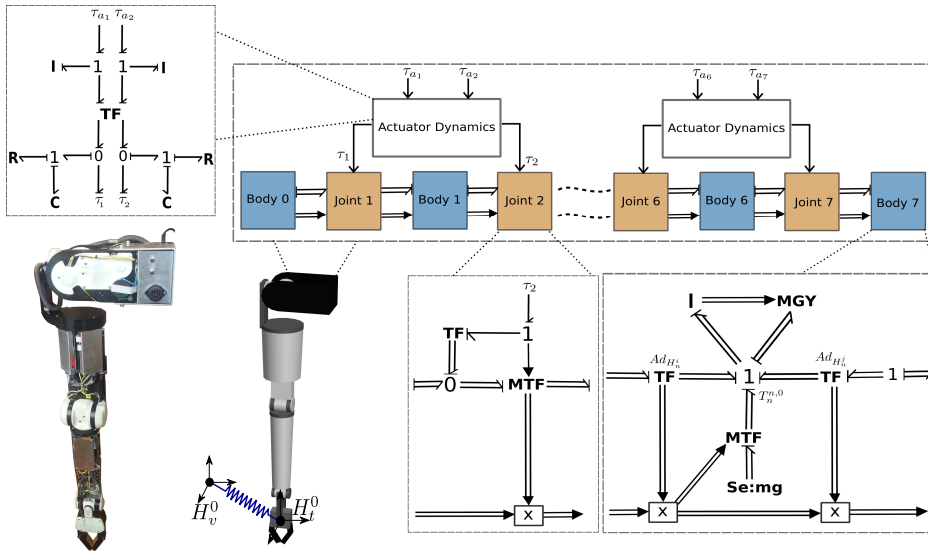


Figure 5.4: The robotic arm and its dynamic model which also indicates the cartesian stiffness defined between current and desired end-effector configurations H_t^0 and H_v^0

Impedance controller design positively contributes to safety by injecting a desired compliance in the system [78] and its passive implementation guarantees stability even during interaction with unknown passive objects in the environment [176]. Given a robotic arm whose current and desired end-effector position and orientation information is represented by a homogeneous matrices H_t^0 and H_v^0 respectively, the cartesian space impedance controller can be physically represented by a multidimensional spring with zero rest length that exerts a force to co-align the two configurations. See Figure 5.4. Damping is also injected in the system to achieve asymptotic stability behavior. In order to obtain satisfactory performance from the robotic arm, the impedance controller is used together with a low level torque feedback loop [3]. The inner torque loop shapes the kinetic energy of the system and minimize the effect of the reflected motor inertia. After testing the controller on the model, it was implemented on the robotic arm and a number of experiments were conducted to evaluate its performance. The cartesian stiff-

ness achieved from the impedance controller, the effect of the torque feedback loop and the motion error of the end-effector under different compliance values were investigated while the robotic arm was made to track a desired operational space trajectory. See the experimental results in Figure 5.5.

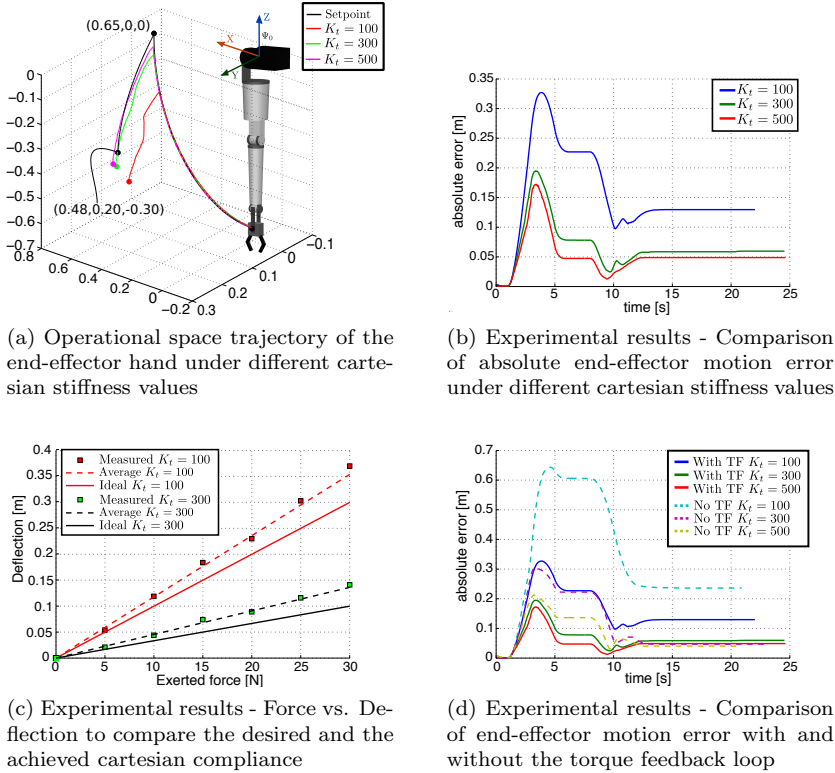


Figure 5.5: Experimental results from impedance controlled robotic arm

5.3.1.2 Mobile platform

The ability of domestic service robots to move around the operating environment immensely boosts their applications and in Bobbie-UT, this vital feature is provided via an omnidirectional mobile platform. Such omnidirectional platforms offer an improved mobility over conventional four-wheeled vehicles because they allow sideway movements, on the spot turns, and complex trajectory following in narrow aisles [83]. The commercially available platform that was chosen for Bobbie-UT utilizes mecanum wheels and can support a payload of $68kg$ with a maximum speed of $0.8m/s$. The platform comes with separate power units to connect additional devices and a desired movement of the platform is executed by low level velocity controllers implemented on each wheel.

The developments on the mobile platform started with implementing a joystick controlled navigation and was extended to support autonomous movement. To realize autonomous navigation, it was necessary for the robot to understand its surrounding environment and identify its location before planning a motion [207]. Thus, the next development on the mobile platform focused on dealing with the simultaneous localization and mapping (SLAM) problem using inputs from a Kinect sensor [212]. The sensor consists of RGB camera and an infrared based depth sensor that can map the operating environment and detect the distance of objects in a typical home environment [49]. Once the operating environment map and the location of the robot inside the map is determined, then an automatic motion planner can guide the robot towards a desired position in the area. Safety requirements during an autonomous or human controlled movement of a domestic robot also demand handling the possible risk of collision with an obstacle while moving in a dynamic environment [207, 50]. The open-source navigation solution implemented on the platform uses a two step solution consisting of global and local planners [125]. The global planner determines the general trajectory towards a desired location and a local planner modifies this general trajectory to deal with any dynamic obstacles.

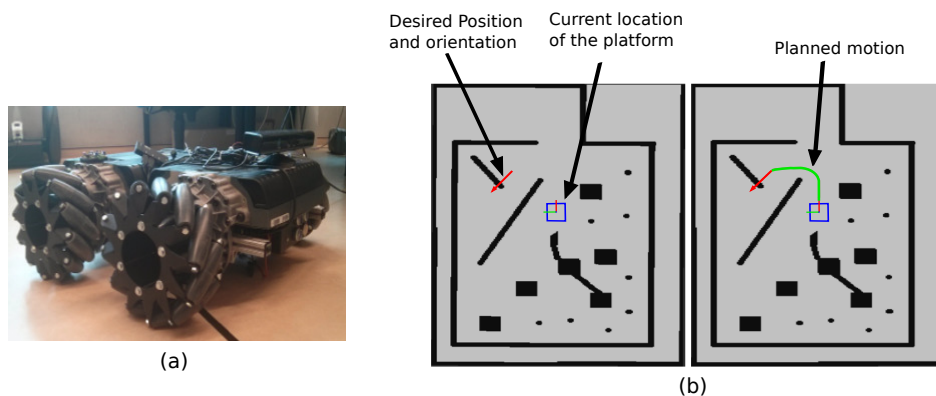


Figure 5.6: (a) The mobile platform with Kinect sensor (b) The motion planner test.

5.3.1.3 Torso and Mechanical Interface Design

The designed torso is composed of an interconnected upper, mid and lower parts. See Figure 5.7. As a central structure that is connected with all the other modular components in the robot, the design of the torso also encompassed the design of the interface between the parts. The upper torso serves as a storage of the robot head actuation components and includes the flanges for the connection of the robotic head and arm components. The mid torso is currently a rectangular aluminum profile used for support and cable guide. The lower torso is used for

support and as the main storage unit for computational and power units of Bobbie-UT.

Such a partitioned design fits into the modularity approach where modifications or improvements on the torso are feasible with the redesign of a specific section. For example an additional degree of freedom that permits bending of the robot can be realized with the replacement of the mid-torso section. Minimizing cost, satisfying sufficient mechanical strength and acquiring favorable ergonomics as well as aesthetics with a human like chest-waist-leg divisions were additional factors considered during the torso design. The torso is also the main component where the risk of tipping over during acceleration or deceleration was evaluated as an important safety requirement. To address this concern, the center of mass was focused sufficiently close to the ground and this has substantially dictated the shape of the torso.

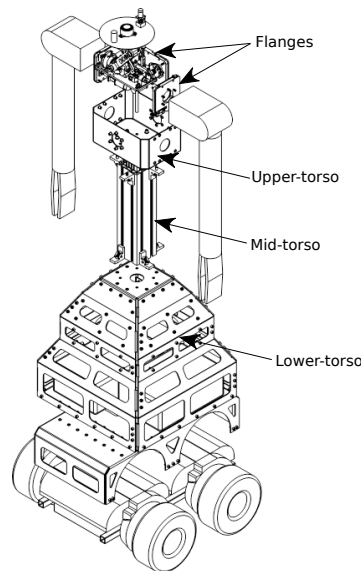


Figure 5.7: Torso of Bobbie-UT

The flange interface is an aluminum body and consists of a female and a male part that lock with each other using a spring loaded slam latch. See Figure 5.8. The flange interfaces were designed to be sufficiently strong so that the risk of unwanted detachment of components is avoided during operation. The mechanical strength of the flanges was analyzed to determine the limits on actuation forces and weight of other robotic arms that can be connected to the torso. Furthermore, it exhibits a stiff behavior so that it is able to transport loads between the interacting parts. Additional factors that influence the flange design include easy mechanical connection and disconnection without the use of tools, support for electrical connection, lightweight construction and elegance. The effectiveness of the flange was

demonstrated after it was manufactured from aluminium and then used to connect the arm and head modules with the torso. The flange interface between the torso and the mobile platform was omitted to reduce the development cost.

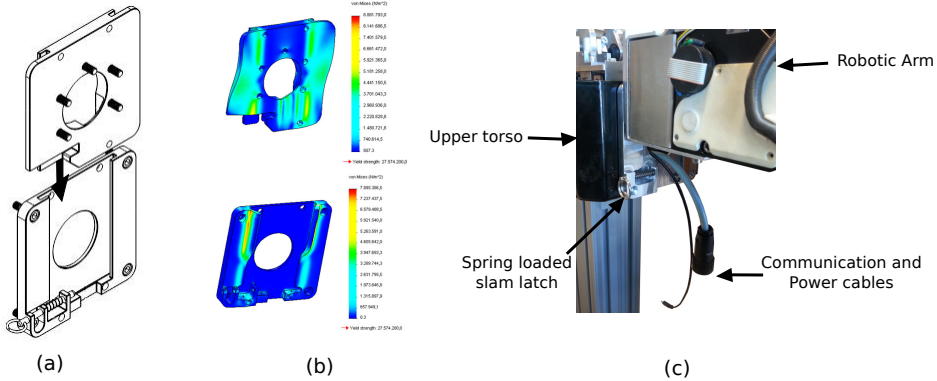


Figure 5.8: The flange designed for Bobbie-UT: (a) male and female parts (b) strength test (c) Connection between arm and torso

5.3.1.4 Humanoid Head and Neck

To make Bobbie-UT an appealing and user-friendly social robot, it is fitted with a robotic head with human-like features. In the past, various humanoid heads have been designed, ranging from stereotypical Hollywood robot heads [6] to very lifelike (android) head designs, complete with flexible skin, movable eyes and abilities to express emotions [13]. After analyzing different humanoid head and neck designs, the Bobbie-UT neck mechanism was designed to be compact, lightweight, backlash free, quiet and statically balanced.

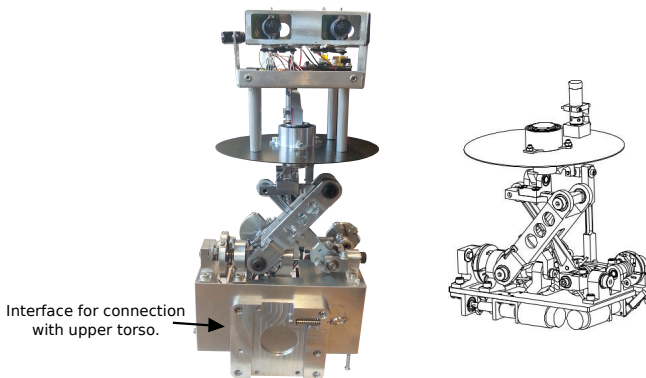


Figure 5.9: Bobbie-UT head and its neck mechanism

A 3-DOF parallel mechanism was designed, so three of the four actuators could be positioned in the base of the neck. This lowers the moving mass as well as the loads on the mechanism. A smaller fourth actuator accounts for the panning motion of the head. The use of gearboxes was avoided, because of the whining noise they make, unavoidable backlash and their cost. Cable drives using low-creep Vectran fibers are used in combination with electric motors to create a back-drivable drive train. There is no backlash to be felt in the entire mechanism, and it moves very quietly because of the cable drives. Static balancing using torsion springs reduces the required actuator torque when the neck is not moving with at least 80%. The total weight of the neck mechanism is 2.9 kg and it is designed to carry a payload of $1.5 \pm 0.2\text{kg}$. This payload can consist of eye cameras, microphones, speakers, a head shell and more.

Vision is another important requirement of domestic robots in which the operating environment as well as the presence of human is recognized by the robot. The main vision capability of Bobbie-UT is provided by two cameras (the eyes) which are connected to servo motors to pan independently and tilt simultaneously. After the camera frames are captured, a two stage image processing tasks were implemented. First the image output of each camera is analyzed to determine the area of interest from the image [89] and then the saliency region is further investigated for the presence of human faces using OpenCV [140]. If a face is detected, the camera is driven by the eye servo so that the spotted face is at the center of the camera image. When needed, additional motion can be accomplished by the neck or even the platform to continuously monitor human users.

5.3.2 Data Processing and Software Architectures

A typical robotic system is comprised of different sensory and actuation devices which are integrated with an embedded software for a controlled execution of tasks. The presence of multiple hardware units in a robotic system is further complicated by fundamental operational requirements such as functional flexibility and dependability. Using a modular design approach of building a robot presents an inherent divide-and-conquer solution for complexity and the hardware units belong to a set of independent modules that manage separate problems. For example, in the case of Bobbie-UT, sensors and actuators of the wheels belong to the mobile platform module and they are used for navigation of the robot inside a human environment.

One suitable methodology of processing the data from the sensory and actuation units is through distributed computing where networked computational units communicate and coordinate their actions [20]. Bobbie-UT also exploits the component centered approach of distributed computing system design to realize a structured architecture where information processing of each modular component is performed by a local computing unit that communicates with a central processor. See Figure 5.10. This construction eases exchange of the robotic components and the multiple communication interfaces on some of the robotic components encourage the development of a modular software that supports all the communication interfaces.

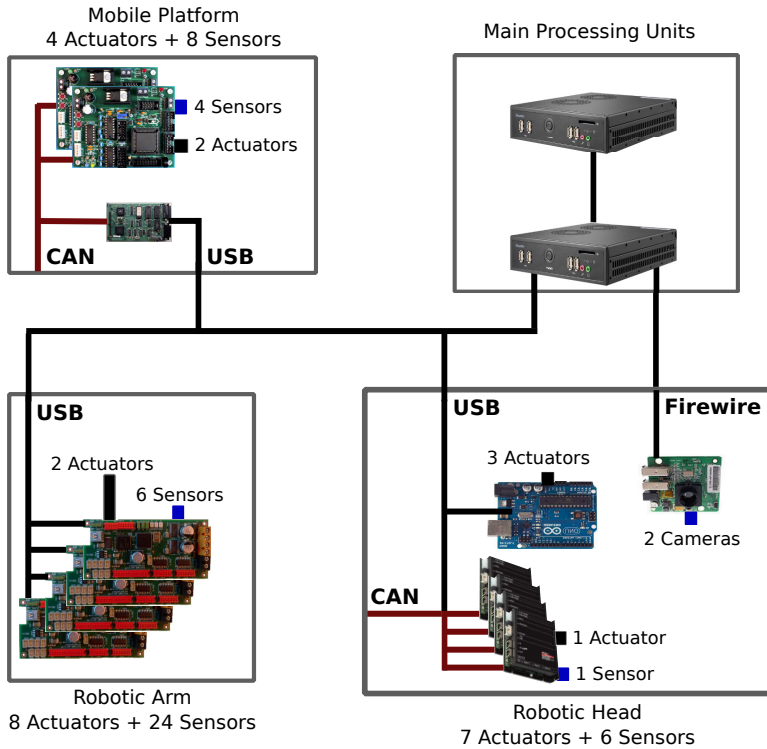


Figure 5.10: Data processing and communication architecture of Bobbie-UT

The robotic software that realizes the full functionality of all the components in Bobbie-UT is implemented on the main processing computers using the component based software development (CBSD) methodology [21]. The core ideology behind CBSD is to design software systems as a composition of one or more reusable components. Building a complete system from a set of software blocks follows in the same line of thought as a modular design approach and offers multiple advantages. CBSD supports the use of off-the-shelf software components that reduce development time, simplify software system modifications and harmonize performance evaluations.

Similar to its partitioned modular hardware design and distributed computing architecture, the robotic software used Bobbie-UT was implemented as a combination of separate software blocks which were developed in-house or reused from other sources. The layered architecture of the software system consists of a low-level communication layer that deals with data exchange with hardware devices, a mid-level processing and control layer which analyzes the data from the hardware and generate control outputs and a high-level application layer that manages the entire operation of the robot. See Figure 5.11.

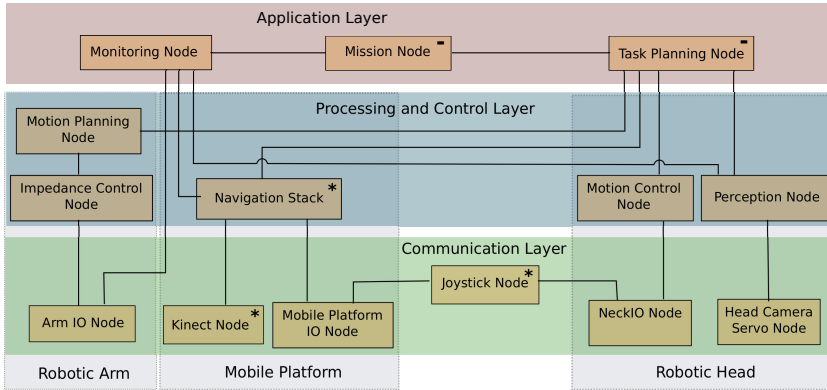


Figure 5.11: Software architecture of Bobbie-UT : The components with * indicate reused components from other sources while those with – are not fully integrated yet.

The Bobbie-UT software was implemented using the Open Robot Control Software (OROCOS) [141] and Robot Operating System (ROS) [157] frameworks. OROCOS is an open source component based software framework that allows the design of real-time software blocks for robot and machine control applications. ROS is also an open-source framework which garnered wide acceptance in the robotics community because of its vast tools and libraries that allow abstraction of hardware, implementation of robot functionality and communication between different processes. The software components of Bobbie-UT that possess real-time requirements were implemented with OROCOS while most of the reused components in the architecture were based on ROS and non real-time.

The development of a complete robotic software using component based methodology requires a systematic approach where separate design issues are addressed independently. A convenient way to present the design considerations of a CBSD is through the 5 Concerns (5Cs): Computation, Communication, Coordination, Configuration and Composition [23][22]. Computation refers to data processing and computing activities of components while communication deals with transfer of data to the computational components. Coordination pertains to how multiple components function together and configuration provides ways of varying behavior of the computation and communication in the system. Composition defines the coupling requirement of the components for completion of its duty. Developing an efficient component based software thus depends on understanding and defining the complete long-term software system with respect to these design ideas.

As seen from Figure 5.11, the in-house software development for Bobbie-UT mainly focused on the design of a communication node for different devices and implementation of a Cartesian space impedance controller for the manipulator. The impedance controller design was first simulated on a model manipulator before a code-generation was used to implement it as a software component. The communication nodes on the other hand followed the 5Cs approach discussed above and were

designed to abstract the modular components of Bobbie-UT. These IO nodes can be considered as a standard software interfaces for the modular components and hence were required to support variability for deployment in multitude of application scenarios. The software pattern used in the design wraps the product specific firmware of the devices in a low-level supervisor component and uses additional software components that individually represent the lowest possible granularity level of the module. See the communication node implementation of the robotic arm in Figure 5.12.

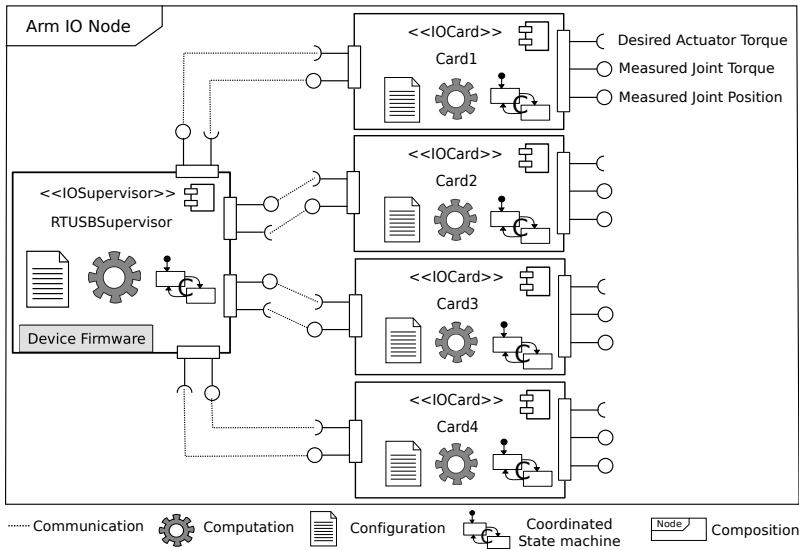


Figure 5.12: Software development structure for a low level IO node of the robotic arm.

The IO node of the robotic arm consists of an *IOSupervisor* component which communicates with the manipulator and four main *IOCard* components that are each responsible for managing all the information regarding one processing unit of the robotic arm. See Figure 5.10. A similar design pattern was also used during the design of the software interfaces for the other modular components. In the case of the robotic head, the same *IOSupervisor* component handles the communication with the motion control cards of the neck and four *IOCard* components process the information related with the four degree of freedoms.

5.4 Discussion and Conclusion

This chapter has discussed the design and development of a modular domestic robot Bobbie-UT which is made of an interconnected arm, head, torso and mobile platform. Manipulation, perception, storage and mobility are the functional requirements addressed by the components separately while impact by manipulator,

collision during navigation and tipping over while accelerating or decelerating are safety issues addressed in the robot design. The modular approach of the robot supports evolution of parts and simplifies the task of building a robot as a system integration problem. Even if the components are developed separately, it should be noted that a full operation of the robot requires identification of the relations that exist between the modules. For example, Inputs from the camera vision are important for manipulating objects with the robotic arm and the current orientation of the arm is important while navigating the platform.

This first prototype of Bobbie-UT is realized with basic functionalities and require additional features to make it a dependable service robot. The first extension needed is a full body control where the world modeling, manipulation and navigation are coordinated during a mission planning and task execution. The robotic arm is equipped with a cartesian space impedance controller but it requires a dynamic motion planner that can avoid impacts with obstacles during manipulation tasks. The use of a single Kinect sensor which has limited field of view and operation range limits the effectiveness of the navigation solution. Hence, including additional robust sensors like laser scanners are needed to deal with shortcomings of the Kinect and acquire redundancy. The lower torso can be slightly modified to add hinges and make its storage area more accessible for maintenance. The mechanical flanges can be further enhanced towards a hybrid design that can support electrical power and data transmissions. The limited range of the camera vision implemented on the robotic head fails to satisfy the safety requirement that the presence of a human in the surrounding environment always be known to the robot. Thus adding an omnidirectional vision system [46, 45] or directional microphones that can allow the tracking of a human in the workspace should be used.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

A national research project Bobbie was started with the goal of designing domestic care robots using modular components. While building a research platform robot Bobbie-UT, additional research goals which can contribute to a successful operation of a domestic robot were set. Each of the goals were discussed in four main chapters of this thesis and the core ideas of the work are summarized with a concluding remark in this chapter. Recommendations for future works on the focus areas of the thesis are also suggested.

6.1 Conclusions

6.1.1 Safety

Before domestic robots are allowed to openly wander around our hall ways, their overall safety must be ensured against well known hazards. People are skeptical about robots that operate in a typical human environment and at the same time they are fascinated by the technology of the “machine humans”. So a safety guaranteed robotic assistant has the opportunity to impress users and gain a wider acceptance. The standard risk based analysis is the right approach to address the issue and a number of research activities have followed this approach to unveil important outputs that contribute to safety of domestic robots. In Chapter 2 a functional safety approach is used to present a brief review of these publications.

In the functional safety approach, overall system safety is investigated by analyzing the proper functioning of its components. Different safety centered robotic system designs were introduced in mechanical design, control system implementation, sensing, motion planning and perception. Analysis of safety related work

should be complemented by valid safety norms which define injury levels of potential injuries. The most significant risk for domestic robots is uncontrolled collision and its resulting injuries can be measured using acceleration, force, energy or power based safety metrics. For robotic manipulators highlighted in this thesis, a lightweight and compliant design has become a standard requirement to address safety. The compliance can be implemented by using physical spring elements at the joints and recently studies are conducted on varying of the stiffness to support highly dynamic task execution. Control systems for human-friendly manipulators are expected to inject compliance for rigid robots and ensure stable operation in an unstructured environment. Sensing and perception are additional components of a robotic system that are important for the robot to understand the surrounding environment it operates in. Multiple sensors are needed to fully represent an unorderedly workspace and their information should be merged to create a unified world model. Motion planning allows for movement of the manipulator and navigation of the complete robot for successful task execution. In general, a motion planning scheme that considers safety should be reactive to imminent changes in the environment.

6.1.2 Controller Design

Controllers designed for human-friendly manipulators should introduce compliance for rigid manipulators, inject damping for proper manipulation and guarantee stable operation even during interaction with unknown objects. Passivity based impedance control belongs to the class of interaction controllers and it can provide a desired compliant behavior and a suitable damping for a manipulator. Passivity of the controlled system is a crucial design requirement that guarantees asymptotic stability of the system during interaction with any passive system. One common observation in the realization of compliant robotic manipulators is that a highly compliant manipulators are safe but display unsatisfactory motion performance and a highly stiff manipulators are unsafe but good in motion tracking. This raises a question on how much compliance is needed for a given safety or performance requirement. Analysis of the desired impedance behavior against these requirements identifies the trade-off between them and determines performance losses for a chosen safety level or safety compromises for a given performance target.

For a performance metric defined in terms of maximum allowed motion error, a model dependent frequency domain based analysis was used to identify the necessary impedance behavior for a simple robotic manipulator modeled as a moving mass. The analysis was then extended to support a cartesian impedance control which supports manipulation in the 6D task space. The multidimensional extension first uses a diagonal cartesian space inertia, stiffness and damping matrices to decouple the translational and rotational motions and apply the ideas from the simplified case on each DOF. Then a worst case design approach of mechatronic system design was used to implement a generalized controller that handles the non-linear inertia of the manipulator. That is, the diagonal cartesian stiffness and

damping parameters that satisfy the desired motion performance are designed for a diagonal inertia which is greater than the non-linear cartesian inertia of the manipulator. Since the motion performance is designed for a higher inertia, it will still be maintained when the impedance is applied on a manipulator which has a smaller inertia tensor. Energy equivalence between the joint and cartesian spaces is used to determine the upper bound diagonal inertia. Due to the configuration dependence of the inertia matrix, the upper bound matrix also varies with the movement of the manipulator and this in turn demands a time-varying cartesian impedance to maintain a desired performance. To preserve the passivity of the system for the variable impedance controller, an energy tank based controller implementation is used. This intrinsically passive realization uses a virtual energy storage tank and ensures that movement of a manipulator is done via a controlled energy flow from the tank.

The design of a safety aware controller for a robotic manipulator requires a meaningful safety metric that describes injury levels of a collision risk. In Chapter 4 energy and power based safety metrics are used to determine appropriate impedance parameters that satisfy an adequate safety requirement. The metrics define the maximum energy and power limits that a human can sustain before an injury occurs. Then the controller monitors the energy of the controlled system and the power flow from the controller to the manipulator and ensures that in case collision happens the energy or power transferred will not harm a person. When an excess energy is detected, the stiffness in the system is decreased to trim the overall energy and when excess power flow is anticipated, the damping is increased to reduce the amount of power flowing to the manipulator. Since the energy and power flow in the system varies depending on the state of the manipulator, a time varying impedance control is needed to preserve the safety requirements. As a result, the energy tank based implementation was also used for both the simplified 1-DOF and multi-DOF manipulators.

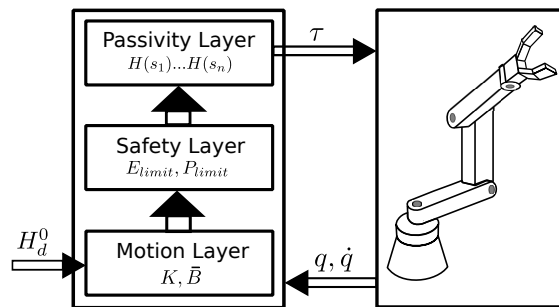


Figure 6.1: Layered control structure with both safety and performance considerations.

The controller design for both performance and safety requirements was validated using experimental results for simple 1-DOF manipulators and simulations for multidimensional n-DOF manipulators. A controller that merges both perfor-

mance and safety considerations can be achieved by using a layered architecture where safety needs have priority over performance. See Figure 6.1. In the combined architecture, a primary motion layer determines the necessary cartesian impedance for a desired performance and afterwards, a second safety layer modifies the cartesian impedance on the basis of energy and power based safety limits. Finally, a passivity layer checks the state of the energy tank to determine the actual joint torque inputs.

6.1.3 Modular Robot

Designing a product as an interconnection of standardized modular components is a suitable methodology to manage construction of complex systems. Such a modular design approach has been adopted by the automotive, information technology and construction industries. Functional requirements of each module, interactions with other components and interface designs which support the interaction are the three main backbones of a modular design concept. The modular concept has also been adopted for the design of robotic systems but it is mainly confined to small re-configurable robot toys. In order to simplify design procedures and support exchange of components among partners, the Bobbie project has emphasized the use of modular design concepts for building a domestic care robot.

The research robot built at the University of Twente, Bobbie-UT, was then designed as an integration of four main modules: head, arm, mobile platform and torso. Each component has its own functionality and the first three components can even function independently. The main functional requirement of the robotic arm is performing manipulation tasks using a control system and safety requirements dictate that a compliant behavior with stable operation is necessary to work in human present areas. Then a passivity based impedance control was implemented on the manipulator after validating the controller in a simulation model. The mobile platform was the main navigation center of the robot and safe operation was achieved by using a Kinect sensor input to implement a reactive motion planner. The robotic head captures information about the environment with the two camera units it possesses and basic human detection is implemented as a safety feature of the component. The head consists of a compliant 4-DOF neck mechanism that allows human-like movements of the head. The torso provides the main structural frame of the robot and is also used for storage of computational, power and actuation units of the robot. Functional requirements dictate a torso design with sufficient mechanical strength during connection with other components while safety considerations focused on avoiding possible tipping over of the robot. The torso by itself is also designed as a modular component with upper, middle and lower partitions that can be modified without altering the rest of the robot. A mechanical flange was then designed to interface the components with each other. A distributed data processing architecture was used in Bobbie-UT and software developments followed a component based design methodology. Software products obtained from outside sources were reused to minimize development efforts.

6.2 Recommendations

Safety

The safety review highlighted possible safety metrics that could be used to define collision injury levels in domestic robots. In order to adopt a standardized metric across the robotics community, a comparative evaluation of these metrics should be performed in a typical domestic robot operational scenario. The safety investigation should consider different environmental conditions and identify acceptable safety norms for potential injury levels. For example, the energy based safety tolerance values are experimentally obtained for serious bone fracture injuries and therefore can not be used for a practical implementation.

Safety improvements in other parts of the robotic system should also be guided by acceptable norms that consider risks beyond collision with a human. Sensory systems that detect the four safety regions in the robot workspace or motion planning features that guide the robot require additional metrics that suit the pending hazard in case of failures.

Controller Design

The passivity based variable impedance controller design proposed in this thesis was validated by experiments for 1-DOF manipulators while those with multiple DOF were limited to simulations. So the first recommendation with respect to the controller design is to experimentally evaluate the proposed implementation on multi-DOF manipulators. One important practical aspect which has to be considered on the experimental validation of the multi-DOF manipulators is friction. The simple 1-DOF experiment for both safety and performance validation was performed on a low friction setup which is often not the case for multi-DOF cases. Thus, unless properly compensated together with gravity, Coriolis and centrifugal forces, friction can negatively influence outputs of the performance based controller designs. On the other hand, the dissipative nature of friction works in favor of safety requirements by decreasing the maximum energy and power flows of the system even below the acceptable value guaranteed by the impedance controller.

The performance based analysis can be further investigated against deviations in the orientation of the manipulator's end-effector from its desired configuration. But comparison of rotations in the operational space is not straight forward like positions and needs meaningful metrics [80]. The safety aware controller design can become a complete safety solution by incorporating force based safety criteria in addition to the energy and power based norms proposed in this thesis.

Bobbie-UT

As a first prototype Bobbie-UT showed the advantages of a modular design and reuse of components for the development of a domestic robot platform. Major

functionalities of the modular components were implemented and further work is needed to improve its operation and dependability.

In order to understand the surrounding environment and identify the four main safety regions, an enhanced perception capability should be implemented by fusing inputs from multiple sensors. The information from the two eyes in the robotic head could be combined to determine depth information of objects in the surrounding environment[11, 108]. The mechanical flange designed can add support for interfacing electrical and data communication across the interface between modules. To reach a level of plug-and-play for the modular parts of the robots, each module should include information regarding its features that should be accessible during connection. High level mission and task planning features are necessary to showcase a realistic task accomplishment that requires multiple modules. For example an object fetching task requires a high level software that coordinates the operation of all modular components as it involves object detection, navigation towards the object, picking the object and passing it to a human user.

Advanced manipulation can be attained on Bobbie-UT by connecting a second robotic arm to it. The resulting multi-arm system can perform advanced domestic chores such as cooking and improves the aesthetics of the robot. Increased acceptance of the robot depends on this aesthetics of the robot which can be boosted by adding a proper cover for all the robotic parts.

Part I

Appendix

APPENDIX A

MODELING ASPECTS OF SERIAL ROBOTIC MANIPULATORS

This appendix addressed modeling of serial chain robotic manipulators and presents computation of some parameters which were used in the impedance controller implementation.

A.1 Modeling

A serial manipulator is constructed as series of rigid links which are connected by actuated joints. Thus model of the robotic manipulator can be done as a combination of rigid body, joint and actuator models as shown in Figure 5.4

A.1.1 Rigid body

The configuration of a rigid body within the moving manipulator can be described by using three body-fixed coordinate frames and a gravitational frame. See Figure A.1. Frames Ψ_i and Ψ_j are describe interaction points of the rigid body with other elements while frame Ψ_k represents the principal inertial frame where the inertia matrix of the rigid body is diagonal. The gravitational frame Ψ_g is located at the same point as the principal inertial frame but its orientation is always fixed with respect to the inertial reference frame Ψ_0

The motion of the rigid body is represented by Newton's law and it is generalized as

$$\dot{\mathcal{P}}^0 = W^0 \tag{A.1}$$

where \mathcal{P}^0 and W^0 are the moment and the wrench acting on a rigid body expressed in inertial frame Ψ_0 .

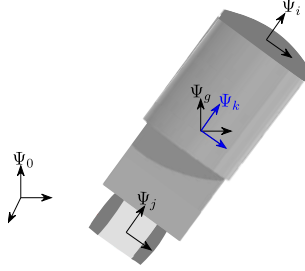


Figure A.1: Four coordinate frames used to describe configuration of a rigid link in a manipulator.

If this equation of motion is expressed in the body coordinate frame Ψ_k , then it becomes

$$\left(\dot{\mathcal{P}}^k\right)^T = ad_{T_k^{k,0}}^T \left(\mathcal{P}^k\right)^T + \left(W^k\right)^T \quad (\text{A.2})$$

where $ad(\cdot)$ is adjoint representation of the Lie algebra $se(3)$, $T_k^{k,0}$ twist of the rigid body with respect to inertial frame Ψ_0 expressed in frame Ψ_k and W^k is sum of all wrenches acting on the body expressed in frame Ψ_k .

This is equivalent to

$$I^k \dot{T}_k^{k,0} = \begin{pmatrix} -\tilde{\omega}_k^{k,0} & -\tilde{v}_k^{k,0} \\ 0 & -\tilde{\omega}_k^{k,0} \end{pmatrix} I^k T_k^{k,0} + \left(W^k\right)^T \quad (\text{A.3})$$

where I^k is the diagonal inertia of the rigid body, $\omega_k^{k,0}$ and $v_k^{k,0}$ constitute the twist of the rigid body and the tilde operator \sim is defined for a vector as

$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \Leftrightarrow \tilde{x} = \begin{pmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{pmatrix} \quad (\text{A.4})$$

In bond graph formulation, this equation can be implemented by using three main elements: an inertial element I that represents the diagonal inertia I^k of the body, a modulated gyrator MGY which computes the adjoint based terms introduced by coordinate transformation and a 1-junction element that represents sum of wrenches. See Figure A.2. Any additional wrench acting on the rigid body can be connected to this junction element after going through a coordinate transformation to the principal inertial frame Ψ_k . That is, joint wrenches which are conveniently expressed in frames Ψ_i and Ψ_j or the gravitational force which is defined in frame Ψ_g have to be transformed to the principal frame Ψ_k before they are used in the motion equation given by (A.2). The transformation is given by

$$\left(W^k\right)^T = Ad_{H_k^x}^T \left(W^x\right)^T \quad (\text{A.5})$$

where W^x , $x = i, j, g$ is wrench is wrench applied on the rigid body expressed in Ψ_x and W^k is its equivalent wrench in frame Ψ_k .

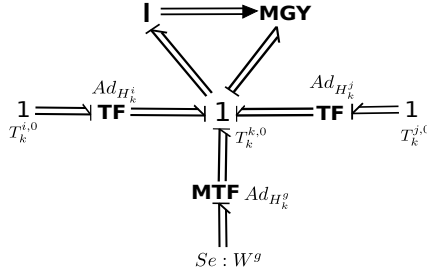


Figure A.2: Bond graph model of a rigid body.

A.1.2 Joint

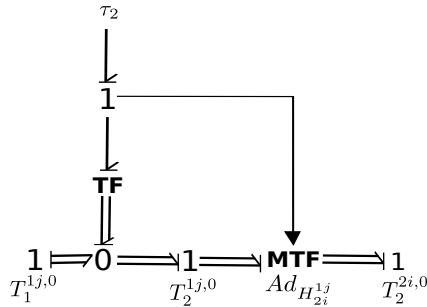
A joint that connects two rigid bodies creates a relative motion between them by using torque inputs from actuators. The wrench applied on both bodies is equal due to Newton's law of action and reaction while the motion of the rigid bodies is related by the following equation.

$$T_a^{i,b} = T_a^{i,0} - T_b^{i,0} \quad (\text{A.6})$$

where $T_a^{i,0}$ and $T_b^{i,0}$ are twist of rigid bodies a and b with respect to inertial frame expressed in frame Ψ_i and $T_a^{i,b}$ is the relative twist between them also expressed in frame Ψ_i .

Since the twist and wrench relation between the two connected bodies is analyzed in a similar reference frame, transformation of interaction variables is necessary to accurately model the joint dynamics.

The relative motion of a joint due to an actuator input can be modeled in bond graph by a 0-junction element while the coordinate transformation which depends on the output of the relative motion is represented by a modulated transformer MTF element. Since the joint in the serial manipulator allows motion in a single DOF, the TF element after the joint torque input implements constraints on the other DOFs. See the final joint model in Figure A.3.


 Figure A.3: Joint model connected between frame Ψ_{1j} of link 1 and Ψ_{2i} of link 2.

A.1.3 Actuator Dynamics

The actuator used on the robotic arm of Bobbie-UT is a differential drive mechanism with a gear assisted harmonic drive. As a result, it exhibits compliance in the joints and its dynamic behavior is influenced by a high gear ratio used on the transmission. The modeling of the manipulator for validation of controller designs has to include these actuation characteristics for properly analyzing the performance of the control system.

In bond graph modeling, the differential drive and the gear transmission can be represented by a transformation element while the remaining joint dynamics on each DOF can be modeled by using basic inertia, compliance and damping elements. See the final actuator dynamics model in Figure A.4.

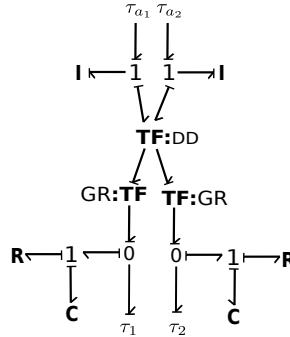


Figure A.4: Actuation dynamics model: Motor inertia I , differential drive $TF : DD$, gear transmission $TF : GR$, joint compliance C and joint friction R .

A.2 Computations

There are some basic computations necessary to implement a cartesian impedance controller on a robotic manipulator. Among them, the Jacobian matrix which gives the Cartesian motion of the manipulator from joint velocities and Inertia matrix which can be used to calculate the total kinetic energy of the manipulator are presented here.

A.2.1 Jacobian

Given n rigid links connected in series chain to form a manipulator and each described by using four coordinate frames in a dynamic model, let frame Ψ_n at the connection point with the next link represent the motion behavior of the link. Then the scalar summation property of a twist dictates that

$$T_n^{0,0} = T_1^{0,0} + T_2^{0,1} + T_3^{0,2} + \dots + T_{(n-1)}^{0,(n-2)} + T_n^{0,(n-1)} \quad (\text{A.7})$$

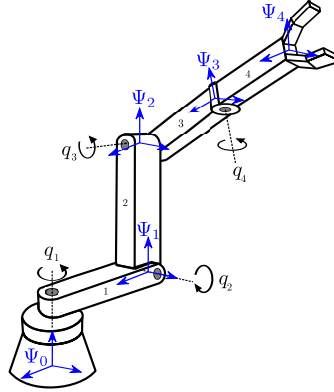


Figure A.5: A 4-DOF robotic manipulator with body fixed coordinate frames per link.

Substituting coordinate transformation of twist in the above equation gives

$$T_n^{0,0} = T_1^{0,0} + Ad_{H_1^0} T_2^{1,1} + Ad_{H_2^0} T_3^{2,2} + \dots + Ad_{H_{(n-1)}^0} T_n^{(n-1),(n-1)} \quad (\text{A.8})$$

Since consecutive links are connected by a 1-DOF joint, the relative twist between them can be represented as

$$T_n^{(n-1),(n-1)} = \hat{T}_n^{(n-1),(n-1)} \cdot \dot{q}_n \quad (\text{A.9})$$

where \dot{q}_n is the joint velocity and $\hat{T}_n^{(n-1),(n-1)}$ is the unit twist of the joint in which for example, a joint with rotation around z axis will have unit twist of $[0, 0, 1, 0, 0, 0]^T$.

Then the equation (A.8) can be written in matrix form as

$$T_n^{0,0} = \underbrace{\left(\hat{T}_1^{0,0} \quad Ad_{H_1^0} \hat{T}_2^{1,1} \quad \dots \quad Ad_{H_{(n-1)}^0} \hat{T}_n^{(n-1),(n-1)} \right)}_{J(q)} \cdot \dot{q} \quad (\text{A.10})$$

where $J(q) \in \mathbb{R}^{6 \times n}$ is the Jacobian of the manipulator and $\dot{q} = (q_1, q_2, \dots, q_n)^T \in \mathbb{R}^n$ is vector of joint velocities.

The homogeneous matrices that describe the configuration of the links can be computed by using their product rule

$$H_b^a = H_c^a \cdot H_b^c \quad (\text{A.11})$$

A.2.2 Inertia matrix

For a rigid body j whose body fixed frame is given as Ψ_j , the kinetic co-energy of the system is expressed as:

$$T_j^* = \frac{1}{2} (T_j^{j,0})^T I^j T_j^{j,0} \quad (\text{A.12})$$

where I^j is the inertia matrix of a body expressed in Ψ_j and the twist $T_j^{j,0}$ expressed in body frame is

$$T_j^{j,0} = Ad_{H_0^j} T_j^{0,0} \quad (\text{A.13})$$

If multiple rigid links are connected to form a serial manipulator, then the total kinetic co-energy will become

$$T_{tot}^* = \sum_{j=1}^n T_j^* \quad (\text{A.14})$$

Looking at the twist summation property in (A.7), the twist of the j^{th} link within the manipulator can be given as

$$T_j^{0,0} = T_1^{0,0} + T_2^{0,1} + \dots + T_j^{0,(j-1)} \quad (\text{A.15})$$

and this can be generalized using the Jacobian matrix as

$$T_j^{0,0} = J(q) \cdot S_j \cdot \dot{q} \quad (\text{A.16})$$

where $S_j \in \mathbb{R}^{n \times n} = \text{diag}(\underbrace{1, \dots, 1}_{j \text{ times}}, \underbrace{0, \dots, 0}_{n-j \text{ times}})$.

Combining (A.12) (A.13) (A.14) and (A.16) gives a total kinetic co-energy of

$$T_{tot}^*(q, \dot{q}) = \frac{1}{2} \sum_{j=1}^n \dot{q}^T S_j J^T(q) Ad_{H_0^j}^T I^j Ad_{H_0^j} J(q) S_j \dot{q} \quad (\text{A.17})$$

$$T_{tot}^*(q, \dot{q}) = \frac{1}{2} \dot{q}^T M(q) \dot{q} \quad (\text{A.18})$$

where

$$M(q) = \sum_{j=1}^n S_j J^T(q) Ad_{H_0^j}^T I^j Ad_{H_0^j} J(q) S_j \quad (\text{A.19})$$

$M(q)$ is the joint space inertia matrix of the manipulator and it is used in the dynamic equation in (3.2).

APPENDIX B

ENERGY TANK BASED CONTROLLER IMPLEMENTATION

The energy tank based controller has been adopted as a suitable implementation technique in this thesis because it maintains a bounded energy in the system and guarantees passivity in a variable impedance controller design. The approach realizes a virtual energy storage element modeled as a preloaded spring with stiffness constant of 1 and ensures that energy to the plant only flows from this source. In this appendix the tank based controller implementation suggested for a simple 1-DOF manipulator in section 4.3 is discussed in detail.

To recap the control system, the main objective of the design is to limit the total energy of the controlled system and power flow from the controller to the plant below a maximum allowed threshold value. As a result unsafe energy is removed by making the impedance controller more compliant and unsafe power is drained by increasing the damping in the controller. The complete implementation is given below.

```
variables          //parameters used

    real s,vs,H;    // state, its derivative and energy of the tank
    real Kc, b;     //Controller stiffness and damping
    real Emax, Pmax; //allowed energy and power limits
    real E, Ef;    //Energy of system before and after correction
    real m,x,v;   // mass, position and velocity of plant
    real xd,xe;   // desired position and position error
    real Pc,Pf;   //Power flow before and after correction
    real Fc, y;   //controller force and controller output
    real u, st;   //flow modulator and sample time

initialequations   //initialequations executed once at the start
```

```

s = 5; //initially 12.5J of energy is stored in the tank.
code    //code section executed every sample time

//controller parameters reset in every execution cycle
Kc = 3.5478;  b = 0.168;

H = 0.5 * s * s;
xe = xd - x; //state of the controller spring

E = 0.5*( (Kc*xe*xe) + (m*v*v));
//Energy limitation determines stiffness parameter
if E > Emax then
Kc = (2*Emax - m*v*v)/(xe*xe);
end;

//Force and power after stiffness correction
Fc = Kc*xe - b*v; Pc = Fc * v;
//Power limitation determines appropriate damping
if Pc > 0 then
if Pc > Pmax then
b = (Kc * xe)/v - Pmax/(v*v);
end;
end;

//Desired output after power and energy corrections
Fc = Kc*xe - b*v;

Ef = 0.5*( (Kc*xe*xe) + (m*v*v));
Pf = Fc * v;

//Passivity check monitors status of energy tank
if H > epsilon or Pf < 0 then
u = -Fc/s;
else
u = 0;
end;

//apply output and compute differential of tank state (4.6)
y = -u*s;
vs = u*v;

//compute new state of tank using discretized integration
s = 0.5*((st*vs)+(st*previous(vs))+2*previous(s));

```

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ABOUT THE AUTHOR

Tadele Shiferaw Tadele was born on Feb 28, 1986 in Addis Ababa, Ethiopia. He attended basic and junior high school in Meserete Hiwot Church School and then completed his senior high school at Meskaye Hezunan Medhanealem Church School. Then, he started a four year Bachelor study in Electrical Engineering at Mekelle University and graduated in July 2007 with great distinction.



He worked as a graduate assistant in the same department for one year before he was awarded a Huygens Talent Scholarship to pursue a graduate study at the University of Twente in the Netherlands. After finishing the necessary graduate courses under the Control Engineering group alongside a final thesis done at Imotec b.v., he graduated in August 2010 with MSc in Electrical Engineering.

Following that, he joined the Robotics and Mechatronics chair at University of Twente as a PhD candidate and started working on a national research project Bobbie. The project targeted the design of a modular and exchangeable domestic robot design that can provide non-critical assistance and his research within the project focused on controller design for human-friendly robotic manipulators that are fitted on these domestic robots.

His research interests are model based design and control of motion systems, robotic manipulation and software development for mechatronic systems. He enjoys football, socializing, internet and piano in his free times.

Successful acceptance and deployment of domestic robots as dependable human assistants in home or office environments depends on their functionality and safety for the user. On the other hand, their commercial viability as a consumer product demands a modular design that can minimize complexity and cost.

